CHAPTER 2

VLF, LF, AND MF SIGNAL PROPAGATION

The radiated field may be a composite of any of three waves propagating from the transmitting antenna: the surface wave which propagates along the earth's surface; the direct wave which propagates directly over line-of-sight distances; and the sky wave which radiates from the transmitting antenna at relatively high angles and reaches the receiver by reflection from ionized layers above the earth. A combination of the surface and direct waves is commonly called the ground wave. Propagation of VLF/LF radio energy is characterized by relatively low ground wave attenuation and by reflection of the sky wave components back to the earth, with very little penetration and absorption at the ionosphere even at high angles of incidence. The ground wave provides most of the signal energy received at distances 100 to 300 km. As distances increase, effects of the sky wave component causes cyclic variations in the intensity of the composite field. The magnitude of the ground wave field component is inversely proportional to the distance. Abrupt changes in magnitude of the ground wave component along the propagation path are possible due to rapid changes in ground conductivity caused by mountainous terrain, large ore deposits, ice fields, sea shores, etc. Long distance transmission in the VLF/LF band is achieved by the sky wave mode alone, which may be considered as resulting from multiple reflections between the earth's surface and the lower regions of the ionosphere at heights between 60 and 90 km. Interaction of the ground wave and multiple sky wave components produces an interference pattern which is dependent upon the ionospheric height. Changes in ionospheric height shift the associated interference patterns, producing some instability that is most evident beyond 1000 km. Figure 2-1 shows typical nighttime interference patterns measured at distances up to 4000 km for frequencies from 10 to kHz. The measured data are compared with the latest theoretical predictions made to 10,000 km.

2.1 GROUND WAVE PROPAGATION

The ground wave is that component of the total received field which has not been reflected (or scattered) from either the ionosphere or troposphere. The ground wave may be conveniently divided into a space wave component and a surface wave component. The space wave is the sum of the direct wave and the ground reflected wave; the surface wave is the direct wave conducted along the surface of the ground. For transmitting and receiving antennas located on, or a fraction of a wavelength above, the ground (always the case in ground-based stations in these frequency ranges), the received ground wave is primarily the surface wave.

Surface-wave attenuation is principally dependent on the characteristics of the surface over which it is propagated. The depth to which the signals penetrate the earth at these frequencies is such that substrata at depths in excess of 100 meters can affect the attenuation and phase of the signal. Figures 2-2 through 2-6 show the computed amplitude of the electric field ground wave as a function of distance from

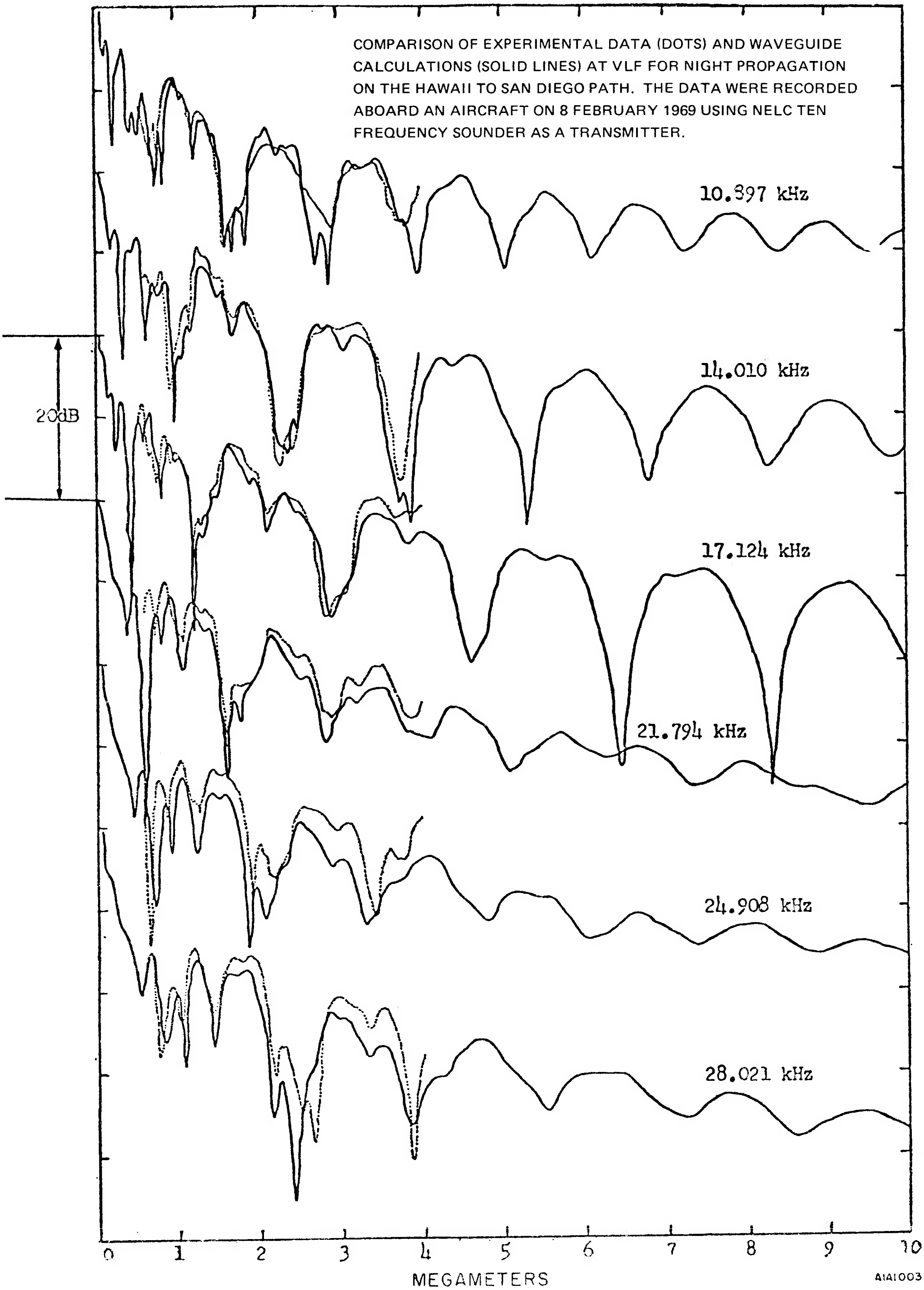


Figure 2-1. Nighttime Interference Patterns

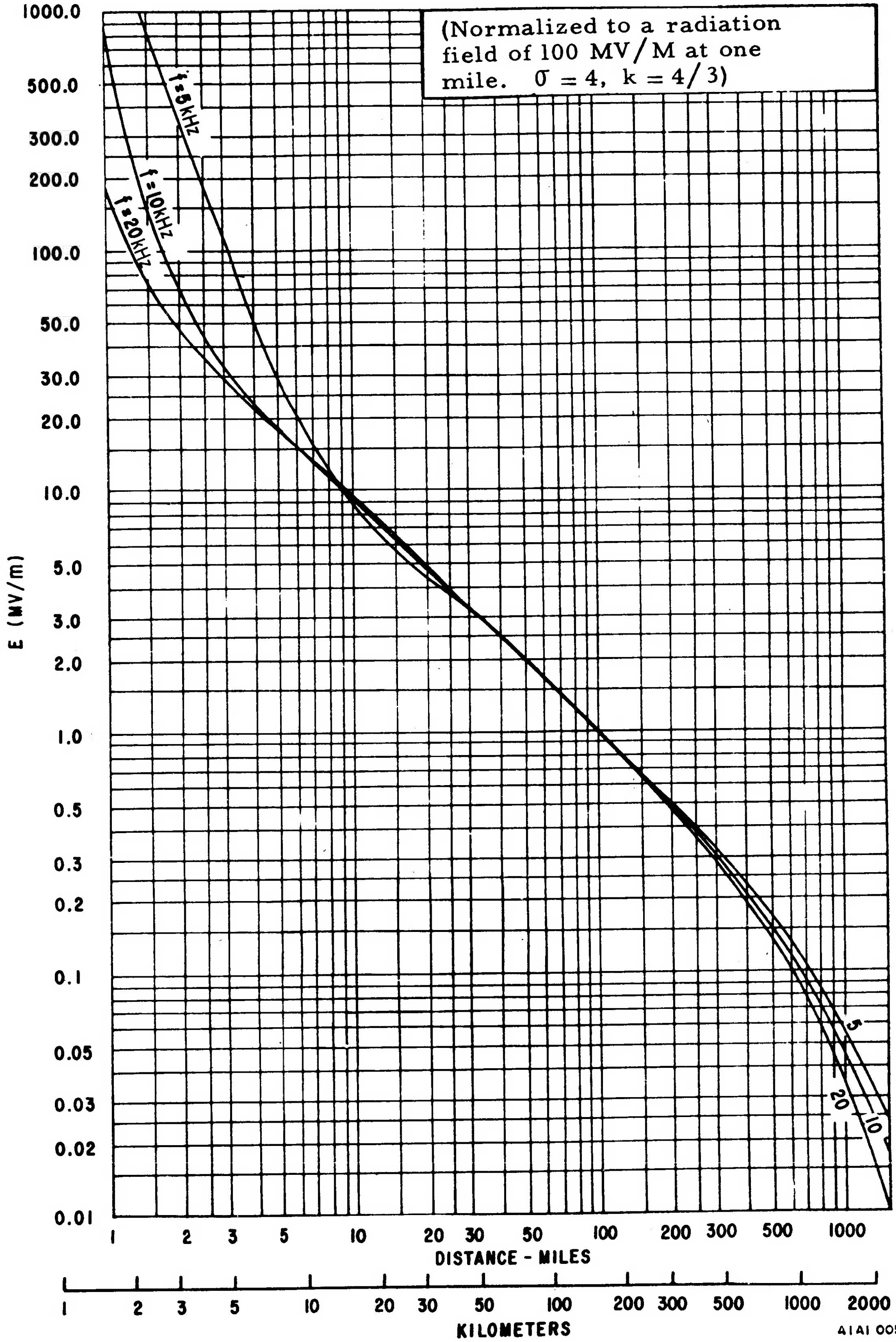


Figure 2-2. Amplitude of Ground Wave Electric Field for f = 5, 10, and 20 kHz at $\sigma = 4$

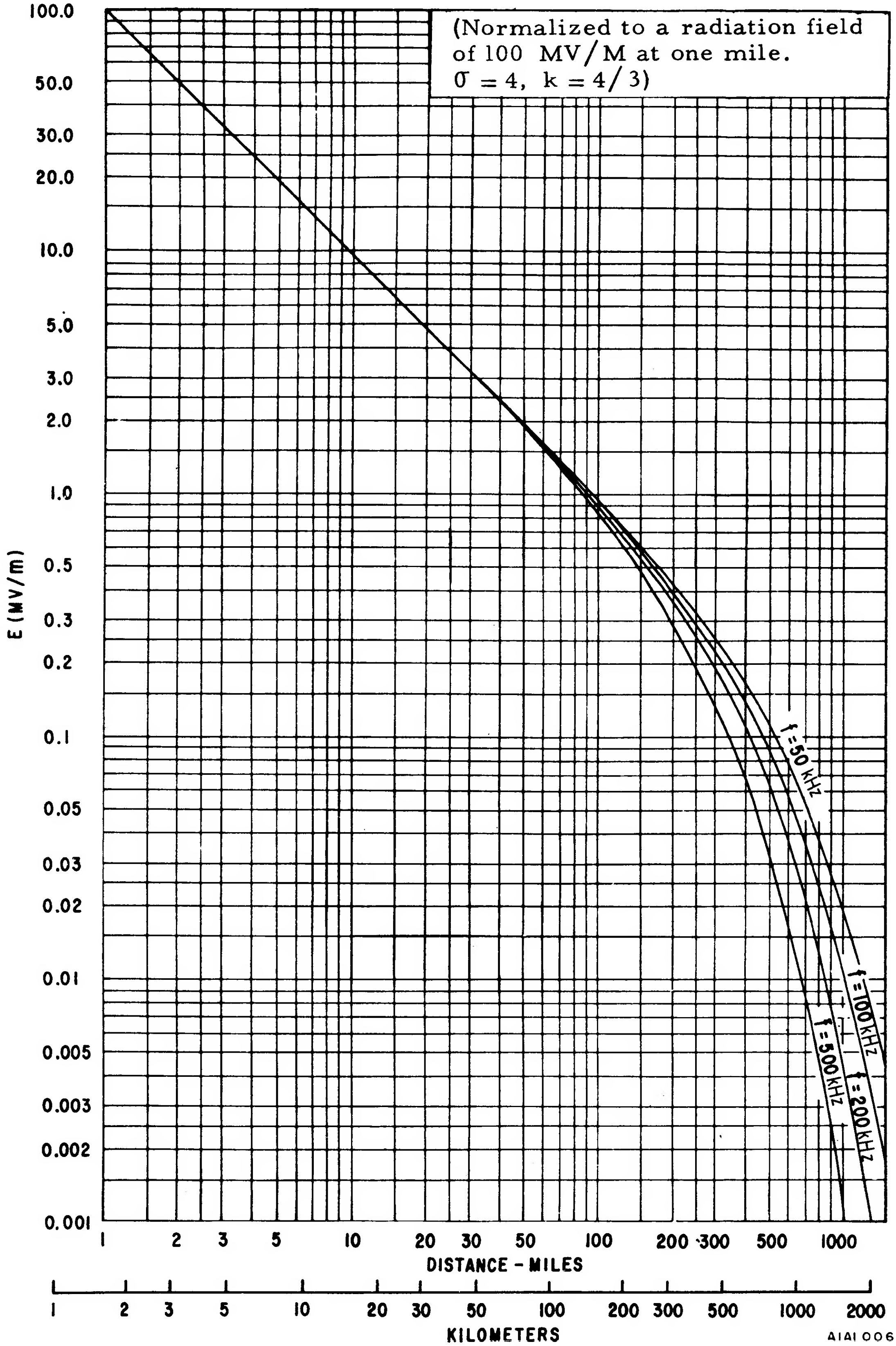


Figure 2-3. Amplitude of Ground Wave Electric Field for f = 50, 100, 200, and 500 kHz at σ = 4

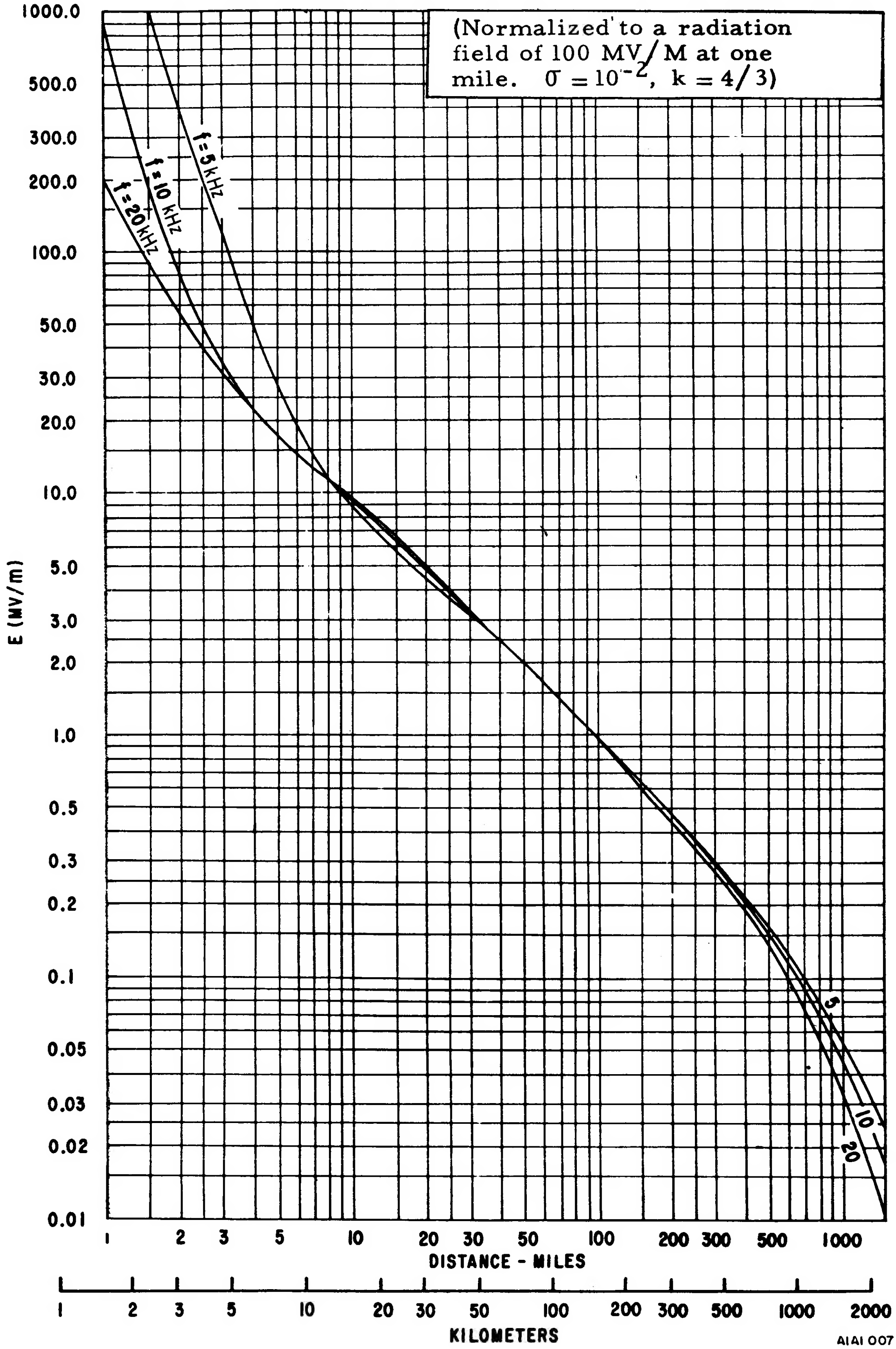


Figure 2-4. Amplitude of Ground Wave Electric Field for f = 5, 10, and 20 kHz at $\sigma = 10^{-2}$

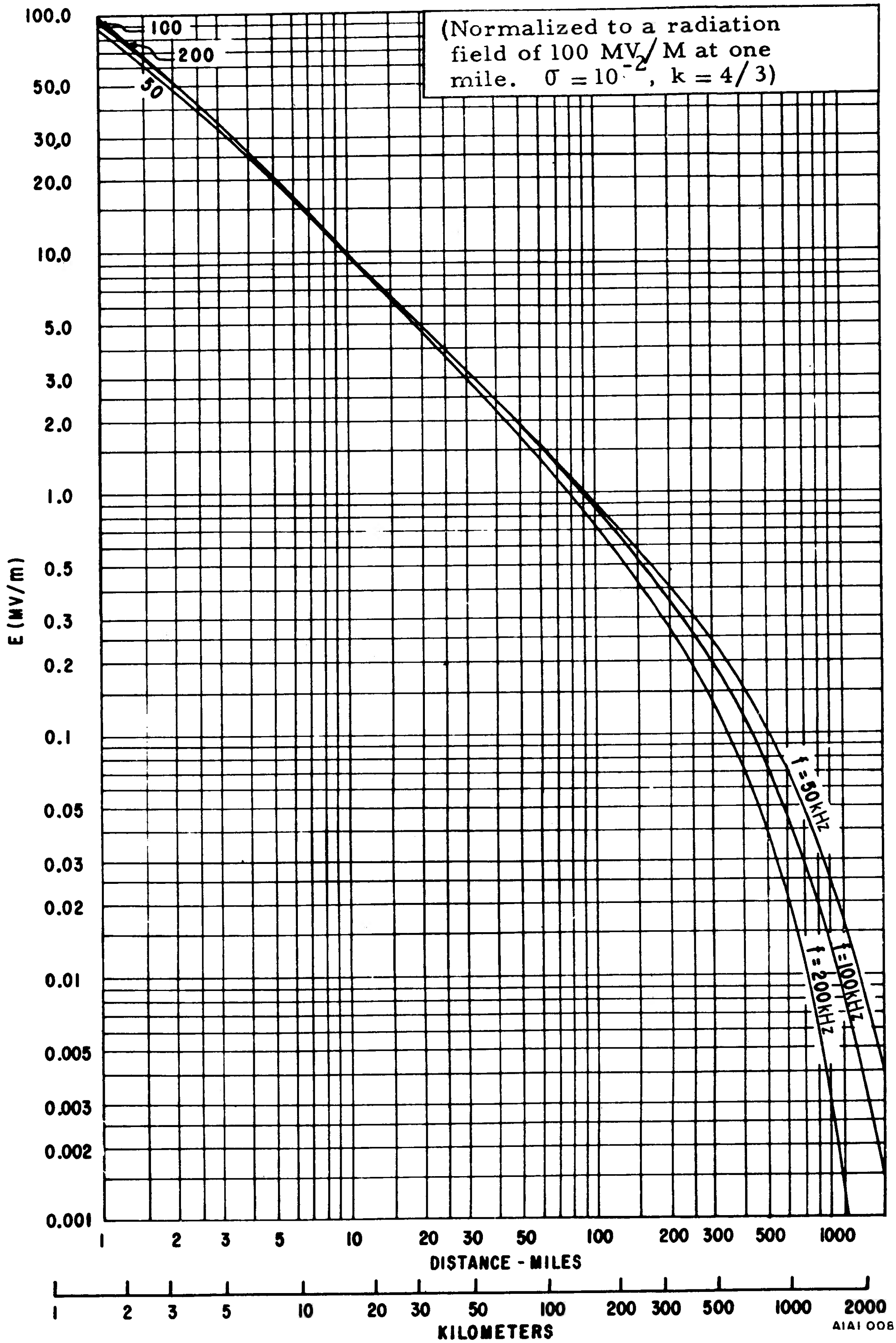


Figure 2-5. Amplitude of Ground Wave Electric Field for f = 50, 100, 200 kHz at $\sigma = 10^{-2}$

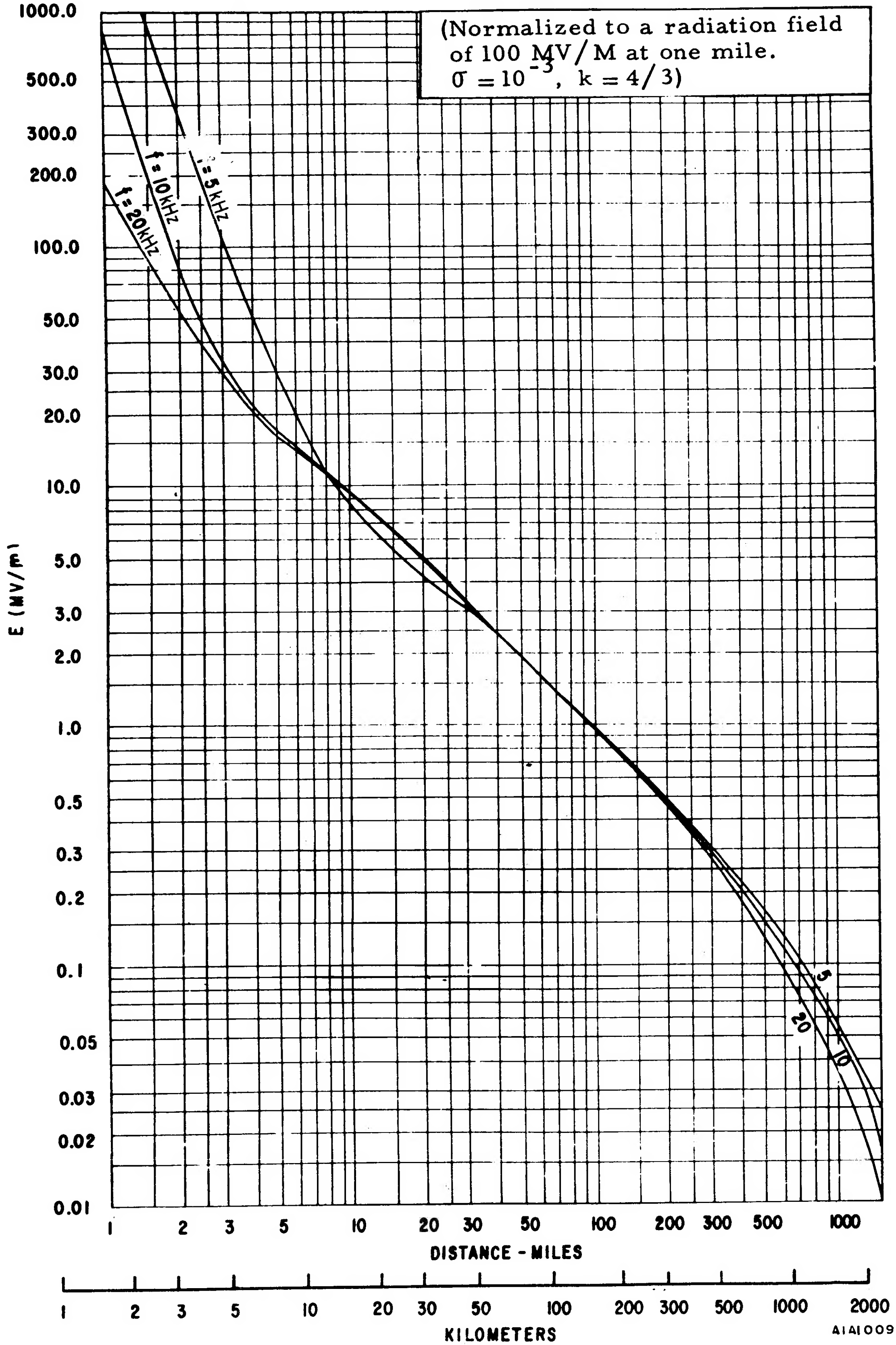


Figure 2-6. Amplitude of Ground Wave Electric Field for f = 5, 10, 20 kHz at $\sigma = 10^{-3}$

the source. The curves have been normalized to a radiation field of 100 millivolts per meter (MV/m) at one mile. Values of conductivity of 4, 10^{-2}, and 10^{-3} mhos per meter (corresponding to sea water, well conducting land, and poorly conducting land respectively) were used in computing the curves.

Ground wave propagated signals are highly stable. Ground conductivity is nearly independent of time, with changes at these frequencies appearing only as very long-term effects. The reliability of ground wave communications is limited principally by either man-made or atmospheric interference.

The strength of the ground wave is influenced by the topography of the path. Large obstacles in the path can attenuate or diffract the ground wave. Roughness of terrain or deviation in the curvature of the earth becomes important when it is an appreciable portion of a wavelength. For most paths, obstacles are unimportant in the VLF/LF band.

2.2 IONOSPHERIC WAVE PROPAGATION

The VLF and LF bands are below the critical frequencies of the lower layers of the ionosphere. In the VLF range the effective D layer is relatively sharply bounded, (i.e. about 5 to 10 km thickness being important) with the reflection coefficient approaching unity. As frequency increases through the LF range the D layer thickness to wavelength ratio increases and the reflection coefficient begins to decrease from unity. The effective reflection height of the D layer varies from about 60 to 90 km with a daytime average of about 70 km and a nighttime average of 85 km. The effective reflection height depends on the ionization levels of the D layer which are maximum during the sunlight hours when ionization rates are maximum and which decreases at night as the ionization rate drops and recombination continues.

In the ELF and VLF regions (up to 20 kHz) frequency spectrum the transmitting antenna can be considered an electrostatic probe in a waveguide. Within 500 km of this transmitting antenna propagation can be analyzed as a radial waveguide consisting of two flat conducting parallel planes. The bottom plane is the earth's surface generally and is a good conductor. The top plane is the ionosphere. This boundary is somewhat absorbent (leaky). The height of the waveguide varies from about 70 km by day to about 90 km by night. In the daytime the only modes normally observed will be TM_{10} through TM_{40}.

At night TM_{50} and TM_{60} will also be excited but there is more attenuation of the higher order modes. This waveguide can be extended from the flat parallel planes to two concentric spheres, bounded only by the earth and the ionosphere. As the wave front progresses beyond 5000 km it is no longer expanding but converging. As the wave front approaches the antipodal point the effects of convergence and absorbtion losses balance. Within this balance boundary around the antipodal point the signal strength increases substantially and provides an additional region of broadcast coverage. For example, the broadcast from Yosami, Japan can be used in the South Atlantic. The broadcasts from Cutler, Maine and from Annapolis, Maryland and from Jim Creek, Washington, and from Balboa, Canal Zone can be used in the Indian Ocean. The Northwest Cape, Australia broadcast can be used in the North Atlantic.

Of course the same propagation phenomena exists regardless of the mathematics used to describe it. Some VLF propagation computations are more easily handled if the waveguide theory is used; some are more easily handled using ray theory. The development of the waveguide theory in the literature is not so well advanced as the ray theory; however an engineer should consider both methods before performing extensive computations.

For further development of the waveguide theory see chapter 7 of "Fields and Waves in Communication Electronics", 1965, S. Ramo, J. R. Whinnery and T. Van Duzer, sections 3.4 and 3.5 of "VLF Radio Engineering", A. D. Watt.

The number of modes which a waveguide will support depends on the size of the waveguide and the frequency of the wave. For wavelengths exceeding the height of the reflecting boundary (D Layer) only the lowest or zero-order mode exists. At wavelengths less than the boundary height, the first-order mode will generally be dominant, but at the upper end of the band higher order modes dominate. Maximum attenuation occurs when the height of the reflecting layer is equal to the wavelength (at approximately 3 to 4 kHz). Attenuation decreases as wavelength is reduced until increasing penetration and associated absorption at the boundaries cause attenuation to rise. The transverse electric (TE) and transverse magnetic (TM) modes have the most influence on VLF propagation. Waveguide mode-calculations compare favorably with experimental measurements at VLF and below. VLF propagation can be treated in the same manner as radio-wave propagation in a waveguide. At VLF, the surface of the earth and the D layer can be considered as forming a concentric spherical waveguide; this waveguide can support TM waves.

Transmission loss to be expected between short vertical electric dipole antennas as a function of range is shown in figures 2-7 through 2-10 for several VLF frequencies. The curves are a composite of the ground wave and sky wave fields. The fluctuations which occur in the waves below about 1500 km are caused by interference between the ground wave and ionospheric wave modes. At ranges greater than about 1500 km the ground wave becomes less significant and the field fluctuations are caused by interfering ionospheric modes. At these frequencies, the fading of the received waves is caused by a gradual shift in the ionosphere during the day and night conditions and thus has a very long period. The transition between day and night is relatively rapid (one hour or two) with deep fades.

No allowance has been made in the computation of these curves for the redistribution of field intensity in space associated with the proximity of the antennas to the ground. The transmission loss given in figures 2-7 through 2-10 is about 6 decibels (dB) lower than it would be if the antenna-height effect on the field had been included. Figure 2-11 shows the effect on the transmission loss associated with the height of the antenna above a perfectly conducting ground.

As can be seen from the values of transmission loss, usable receiving power levels can be expected at ranges beyond the antipode (diametrically opposite side of the globe; about 12,500 miles circumferentially) with reasonable radiated power. Thus, it is possible for multipath-interference to occur from signals arriving via the great-circle path corresponding to transmission in the opposite direction. Since the earth and ionosphere are spherical shells, ionospherically-reflected waves tend to converge

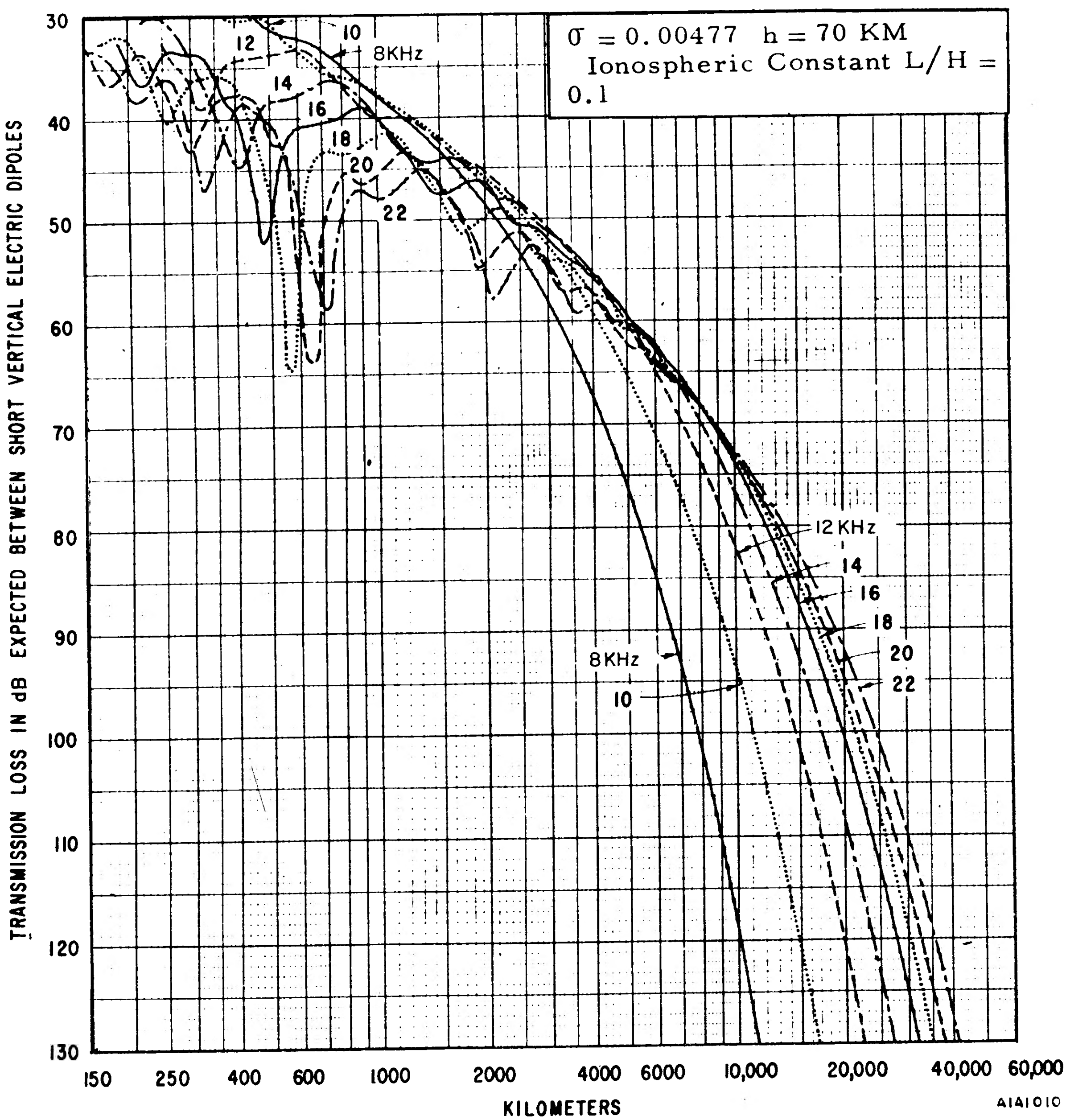


Figure 2-7. Transmission Loss Expected Between Short Vertical Electric Dipole Antennas At Day Over Land (Typical)

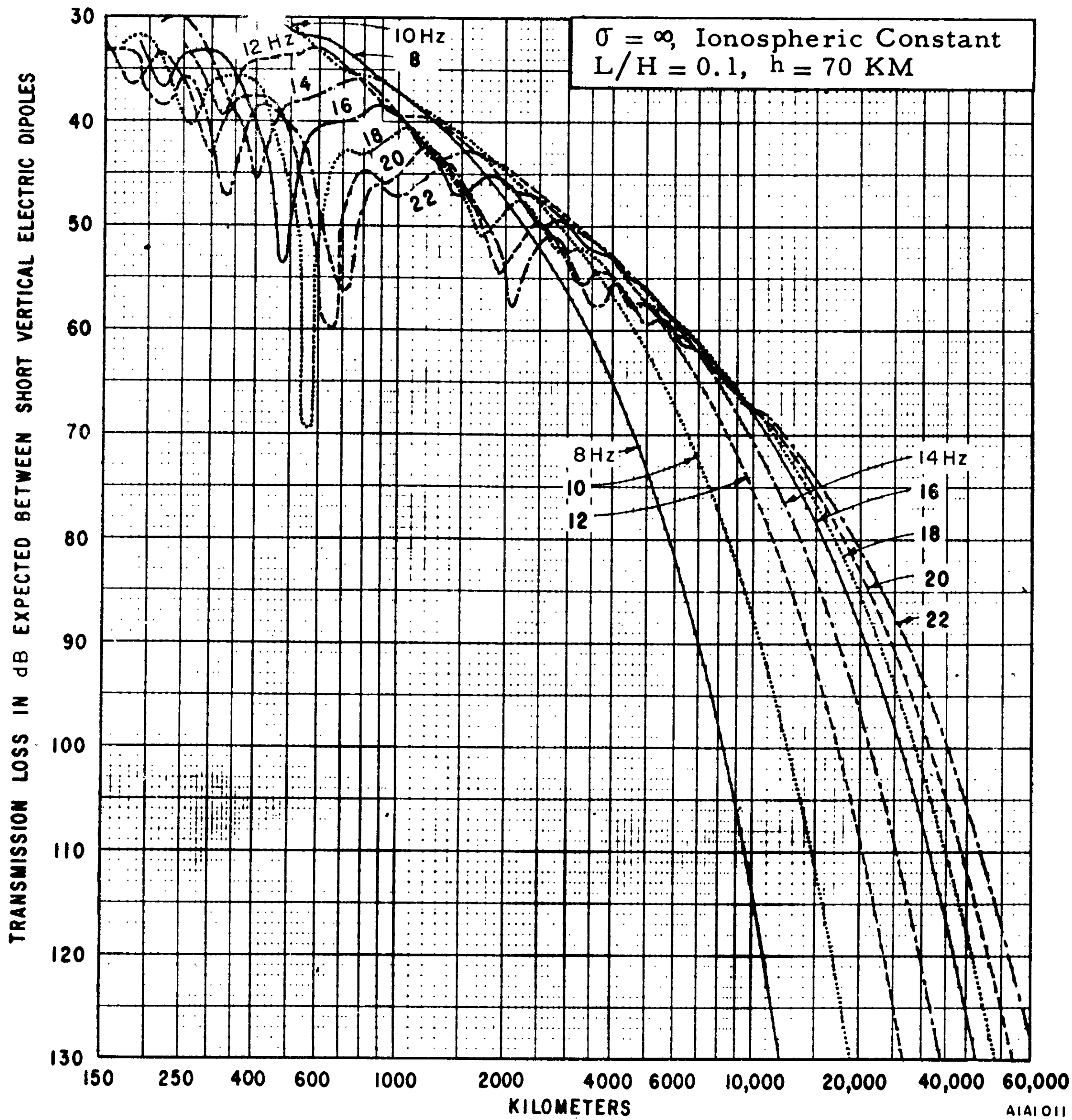


Figure 2-8. Transmission Loss Expected Between Short Vertical Electric Dipole Antennas At Day Over Sea Water (Typical)

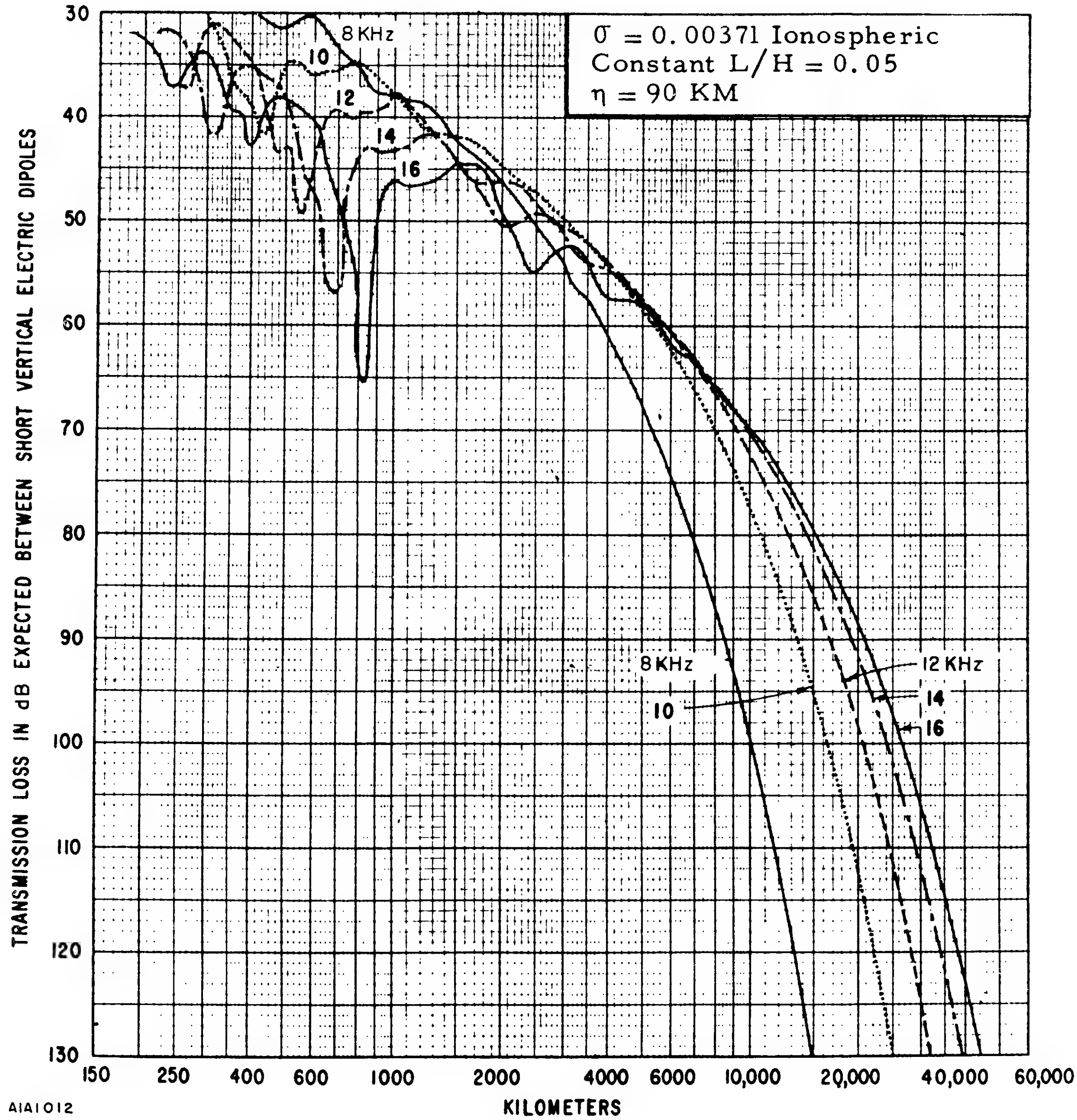


Figure 2-9. Transmission Loss Expected Between Short Vertical Dipole Antennas at Night Over Land (Typical)

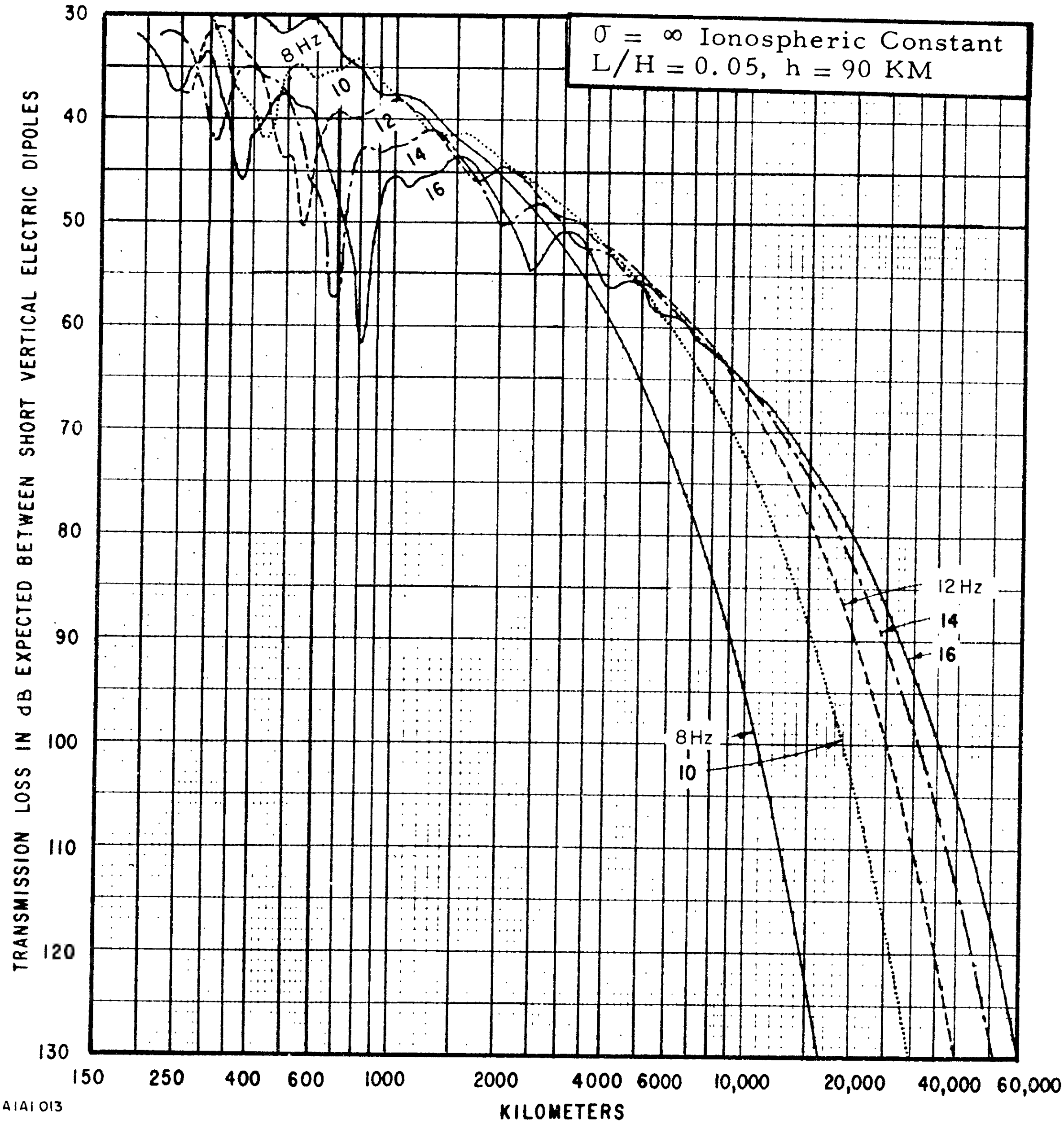


Figure 2-10. Transmission Loss Expected Between Short Vertical Electric Dipole Antennas At Night Over Sea Water (Typical)

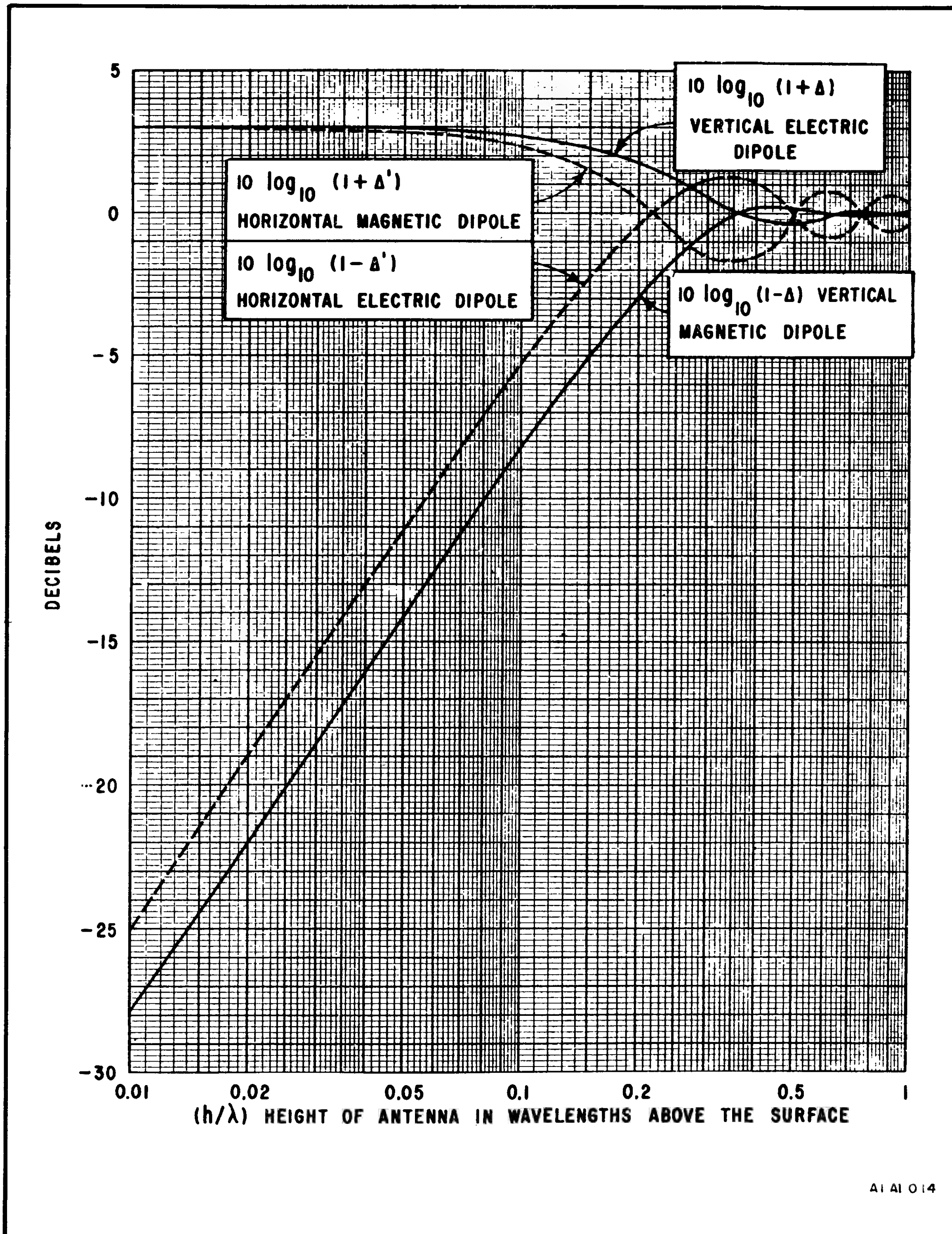


Figure 2-11. Transmission Loss Arising From a Change in the Radiation Resistance of Short Dipole Antennas Near a Perfectly Conducting Surface (Typical)

near the antipode where the great-circle paths converge. This convergence provides considerable increase in signal level in the vicinity of the antipode. Figures 2-12 and 2-13 show the median transmission loss at 20 kHz for an overland-path under both day and night conditions. The effect of focusing can be seen in the decrease in transmission loss in the vicinity of the antipode.

Between 30 and 300 kHz,a gradual transition occurs in which the range where the ground wave dominates the sky wave gradually increases to a maximum at about a few thousand km. With increasing frequency the ionosphere becomes less like a sharp boundary. The radio waves penetrate the lower ionosphere to a considerable depth and attenuation by ionic absorption increases rapidly. Refraction of the radio waves occurs in the D and E layers at heights from 70 to 110 km. The ionization in these layers appears to be a nonhomogeneous, turbulent ionized region which drifts with the wind. The variation in ionization-density causes the radio waves to arrive at the receiver over many different paths. The received signal is thus made up of many signal components of varying amplitudes and phases. As the wavelengths become shorter, the paths over which the signals arrive vary in electrical length by several radians and the phase of the arriving waves can be considered as randomly distributed in time. Waves of randomly distributed phases will combine to produce a field at the receiver which is Rayleigh-distributed in amplitude.

The median transmission-loss expected between short vertical electric dipoles is shown in figures 2-14 through 2-19 for frequencies of 50, 100 and 200 kHz. Values are shown for both ground wave and several ionospheric modes for land and sea paths. The mode, represented by "m" on the curve, corresponds to the number of ionospheric reflections along a great-circle path between the source and the receiver. To determine the expected median transmission loss for continuous wave transmission, convert the transmission loss into power ratios and add the powers of the modes of importance. The various modes should have random relative phase so that the median value of the sum will be the sum of the median values of each mode.

2.3 ATTENUATION

Mathematical description of long distance VLF/LF propagation characteristics has been a topic of controversy since 1911. The original field formula was the empirical Austin-Cohen equation. Later work gave attention to the possible propagation paths and their interactions as determined by the geometry of the earth-ionospheric space. A more sophisticated approach, based on the mode theory developed in 1956, has supplanted much of the earlier work in VLF/LF. In particular, J. R. Wait of the National Bureau of Standards has given an exhaustive exposition of this approach.

Wait's formula for the vertical electric field strength of the N^{th} waveguide mode at distances greater than 1000 nm from a radiating vertical electric dipole is given by:

$$\epsilon_N = \frac{65.11 \times 10^3}{H} \sqrt{\frac{P_R}{F \sin \frac{D}{R}}} \; 10^{\frac{-\alpha_N D}{20}}$$

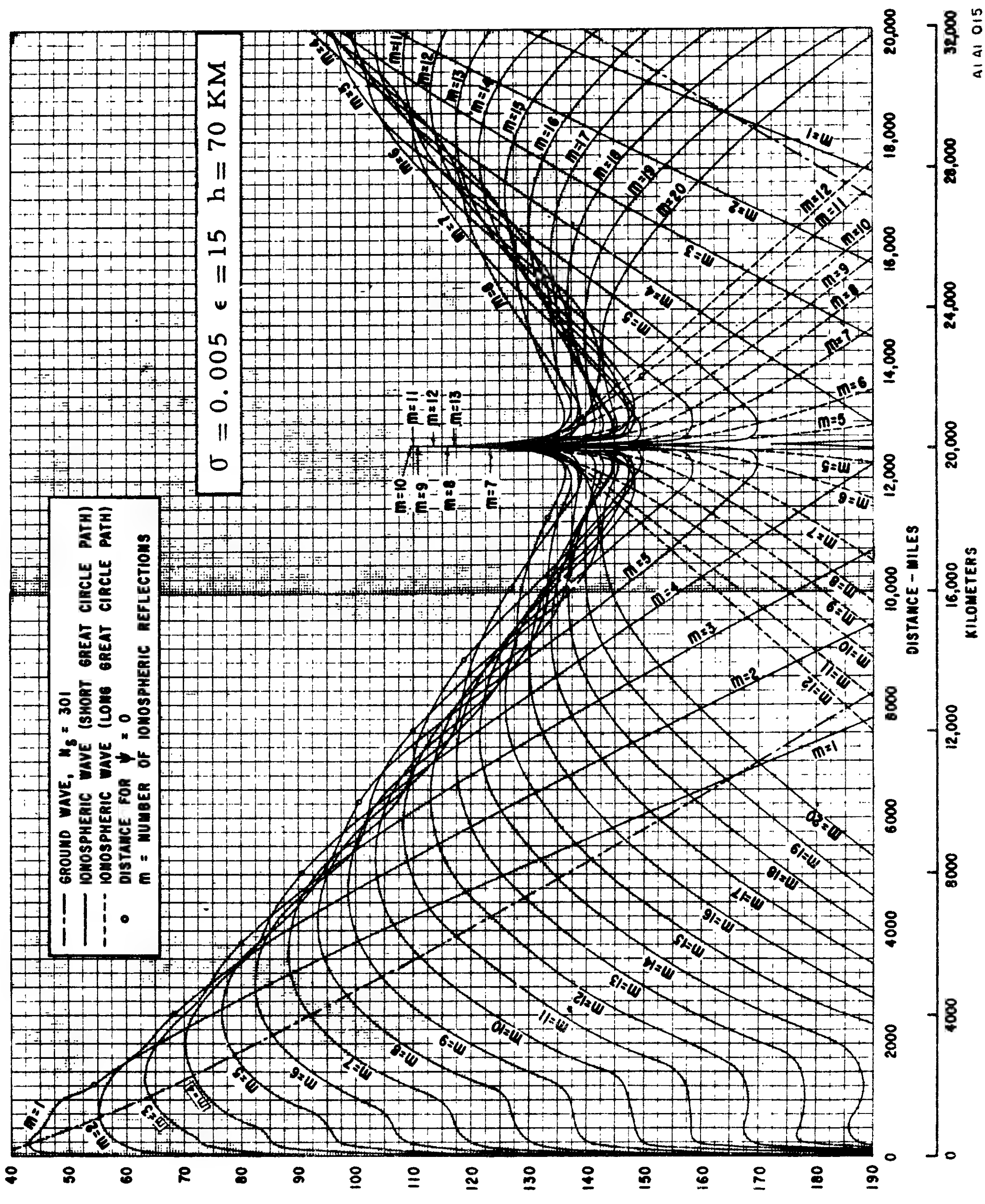


Figure 2-12. Median Daytime Transmission Loss at 20 kHz (Typical)

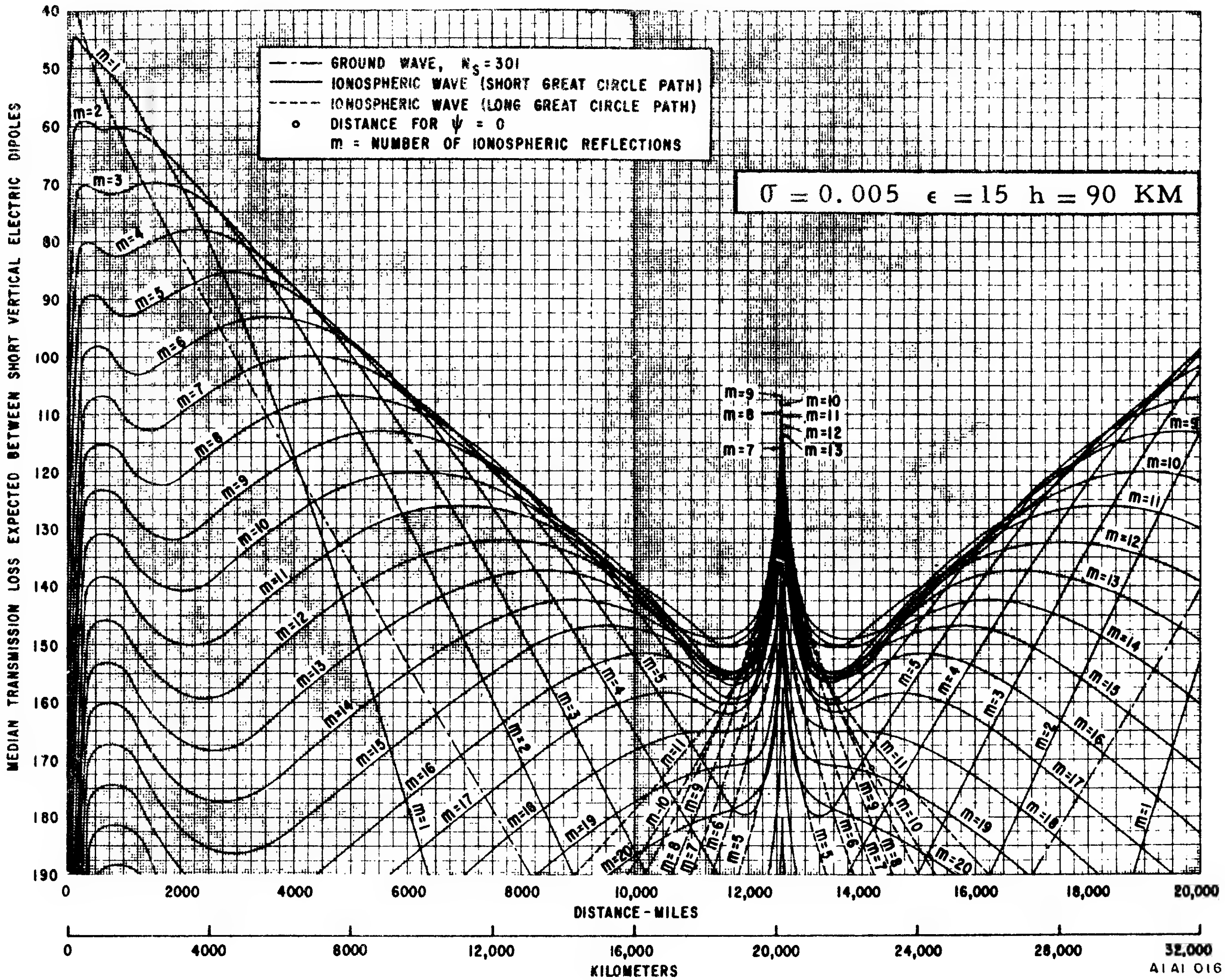


Figure 2-13. Median Nighttime Transmission Loss at 20 kHz (Typical)

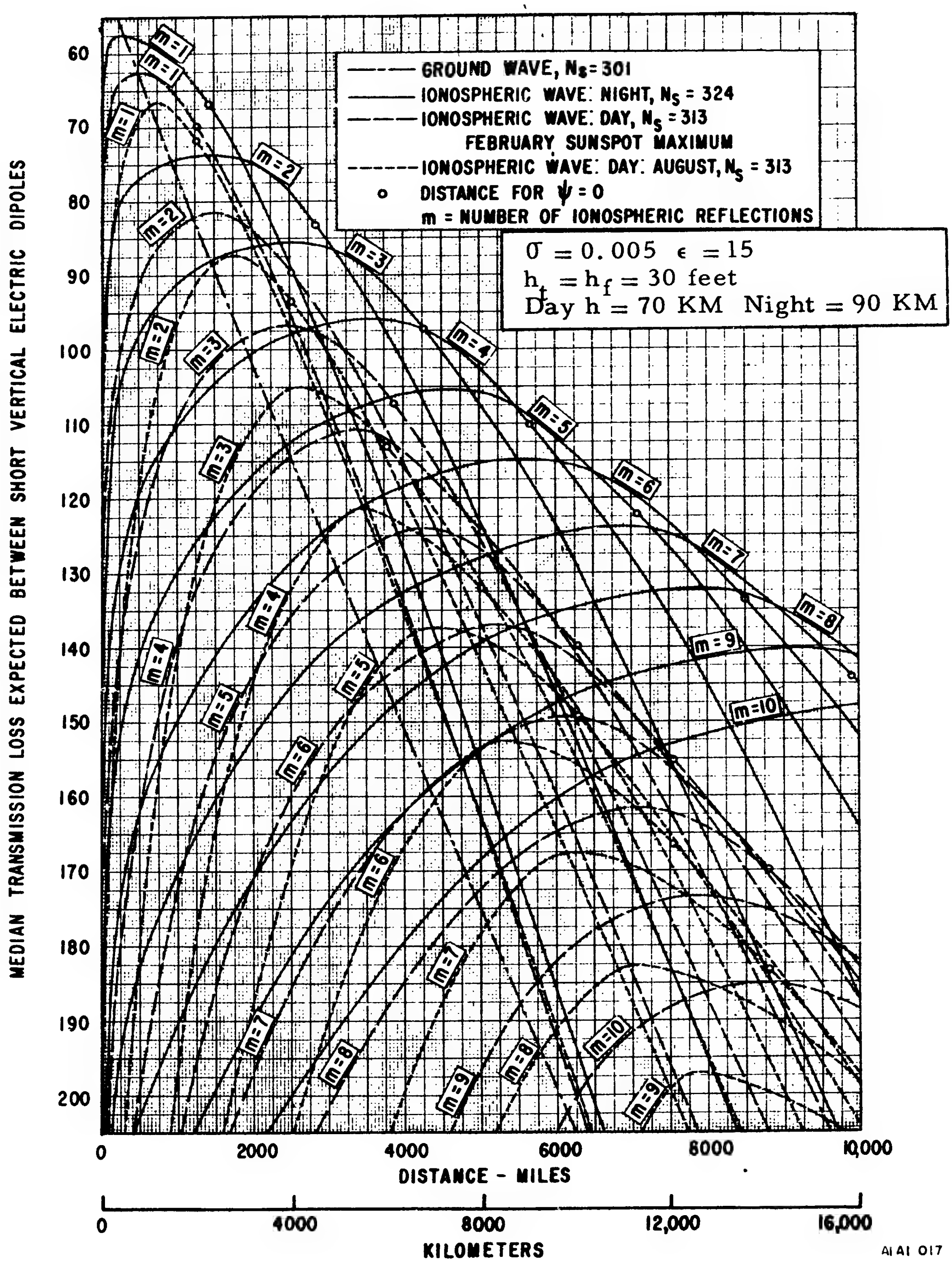


Figure 2-14. Median Transmission Loss Over Land at 50 kHz (Typical)

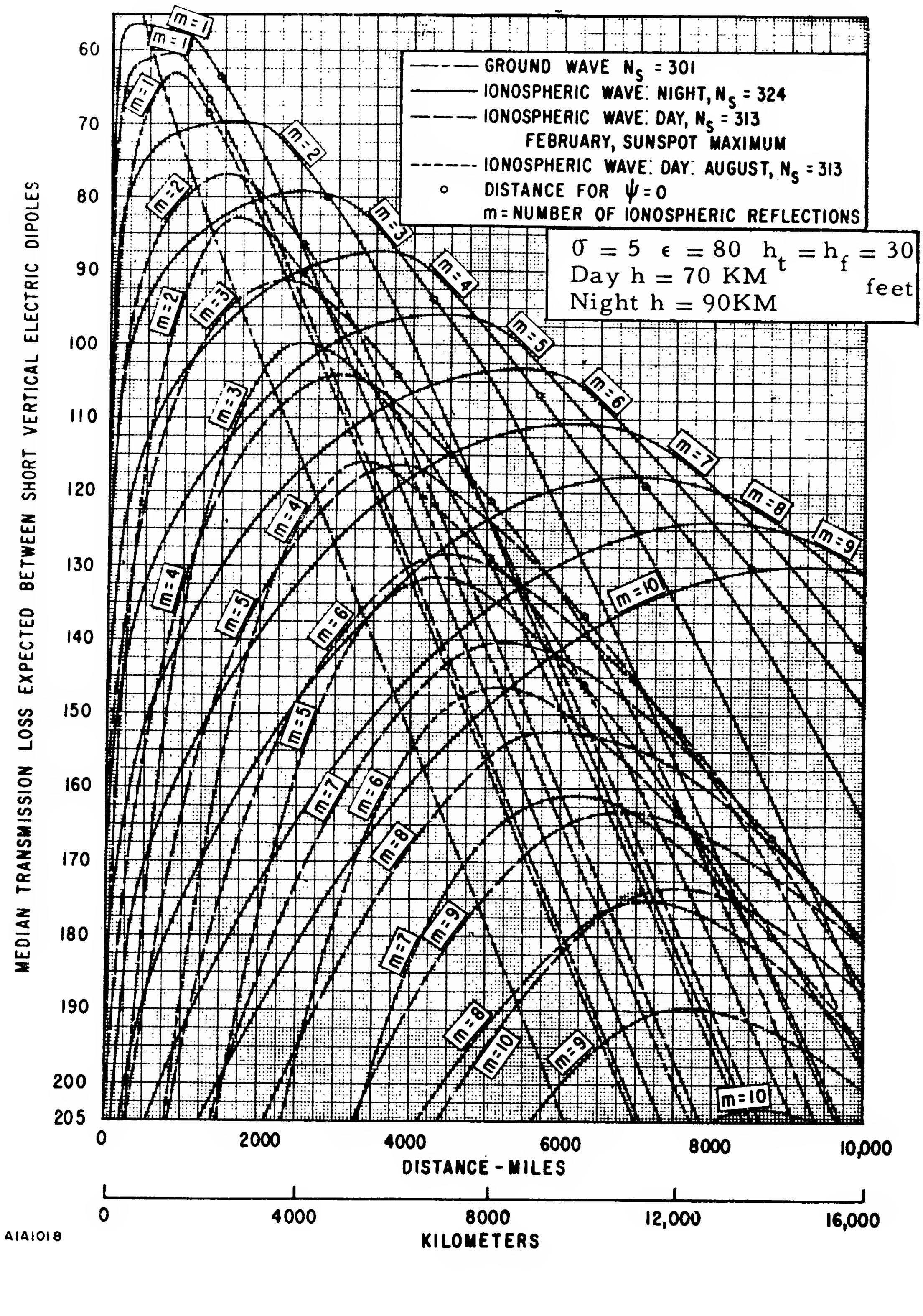


Figure 2-15. Median Transmission Loss Over Sea at 50 kHz (Typical)

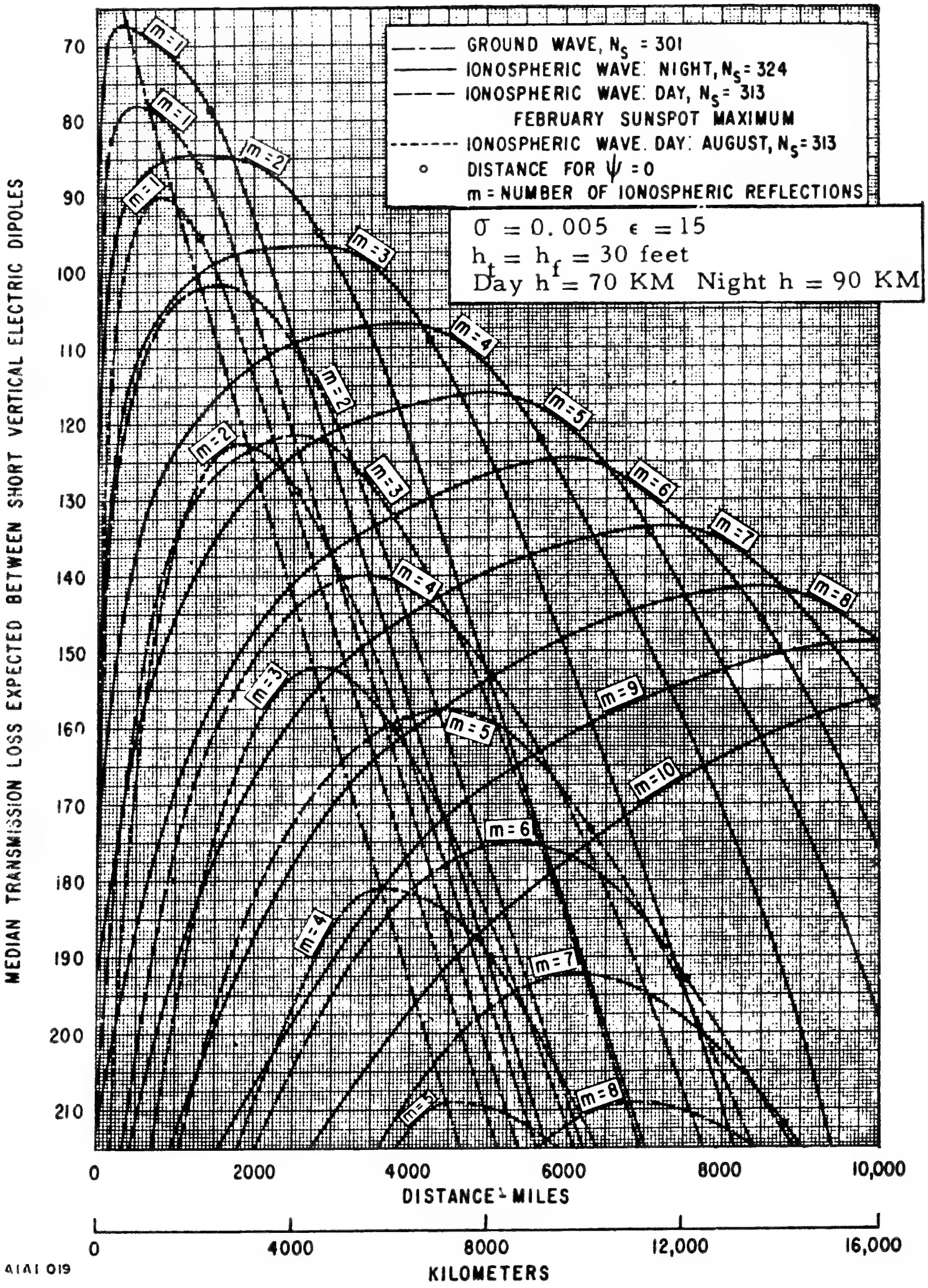


Figure 2-16. Median Transmission Loss Over Land at 100 kHz (Typical)

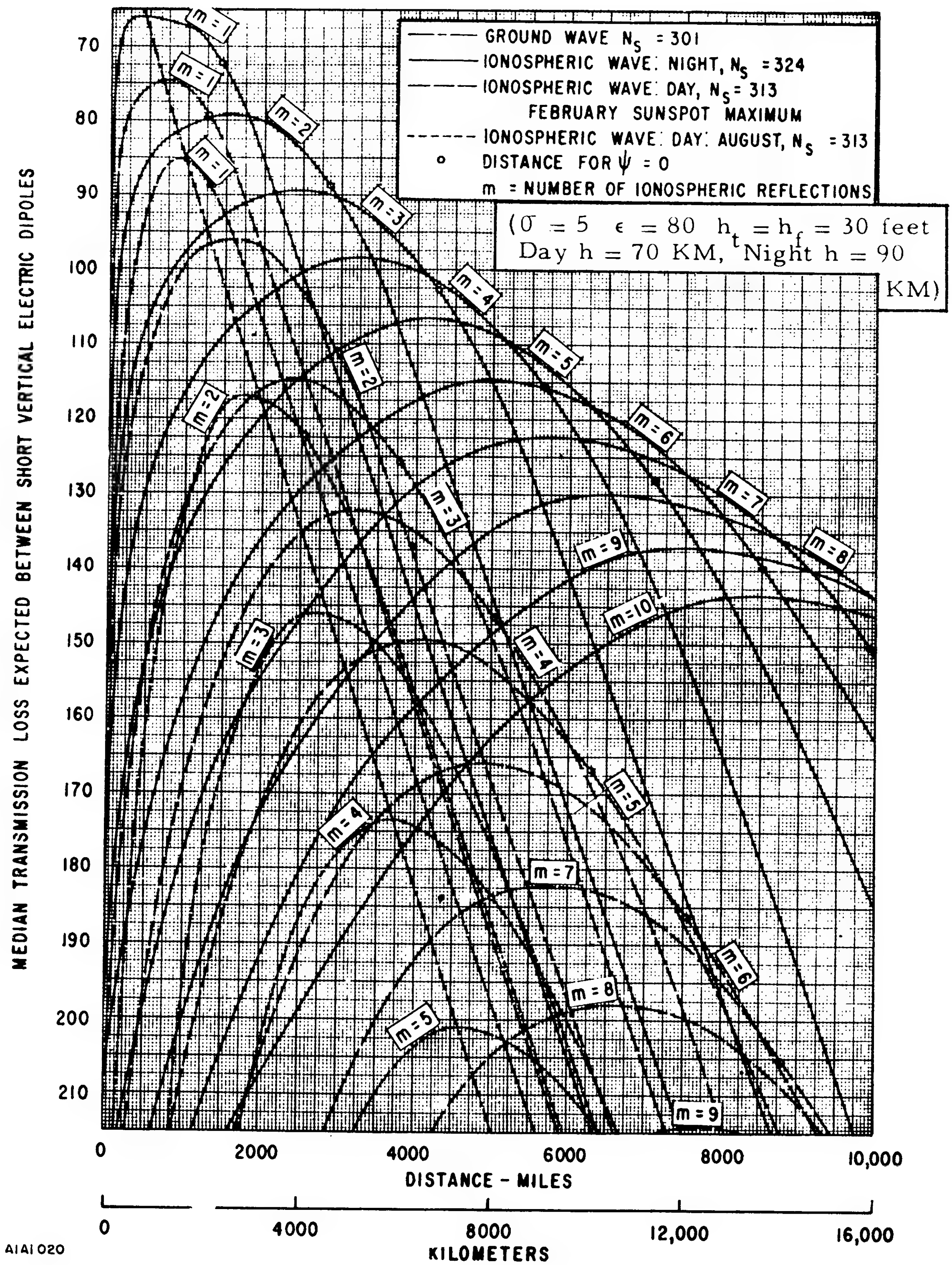


Figure 2-17. Median Transmission Loss Over Sea at 100 kHz (Typical)

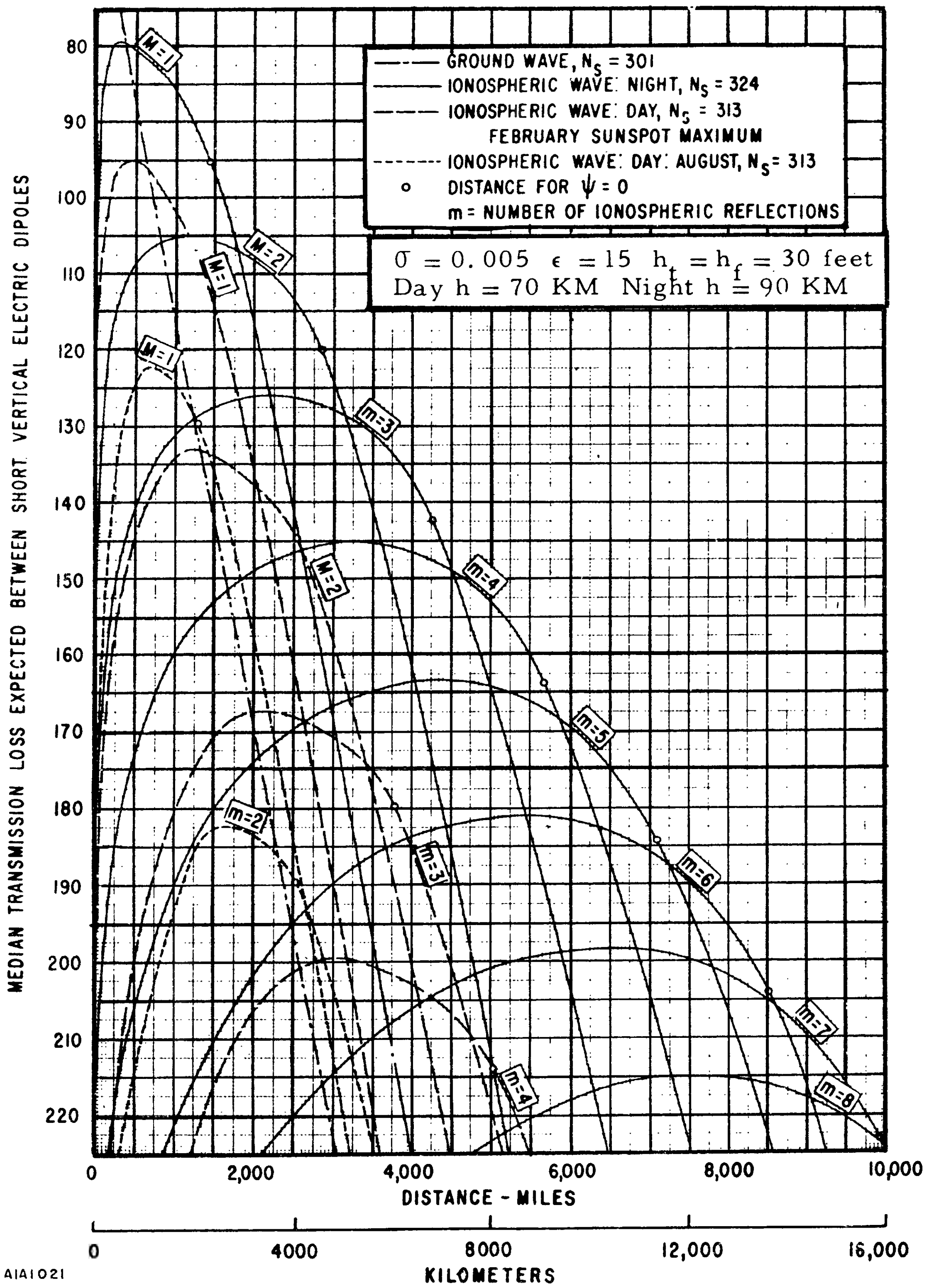


Figure 2-18. Median Transmission Loss Over Land at 200 kHz (Typical)

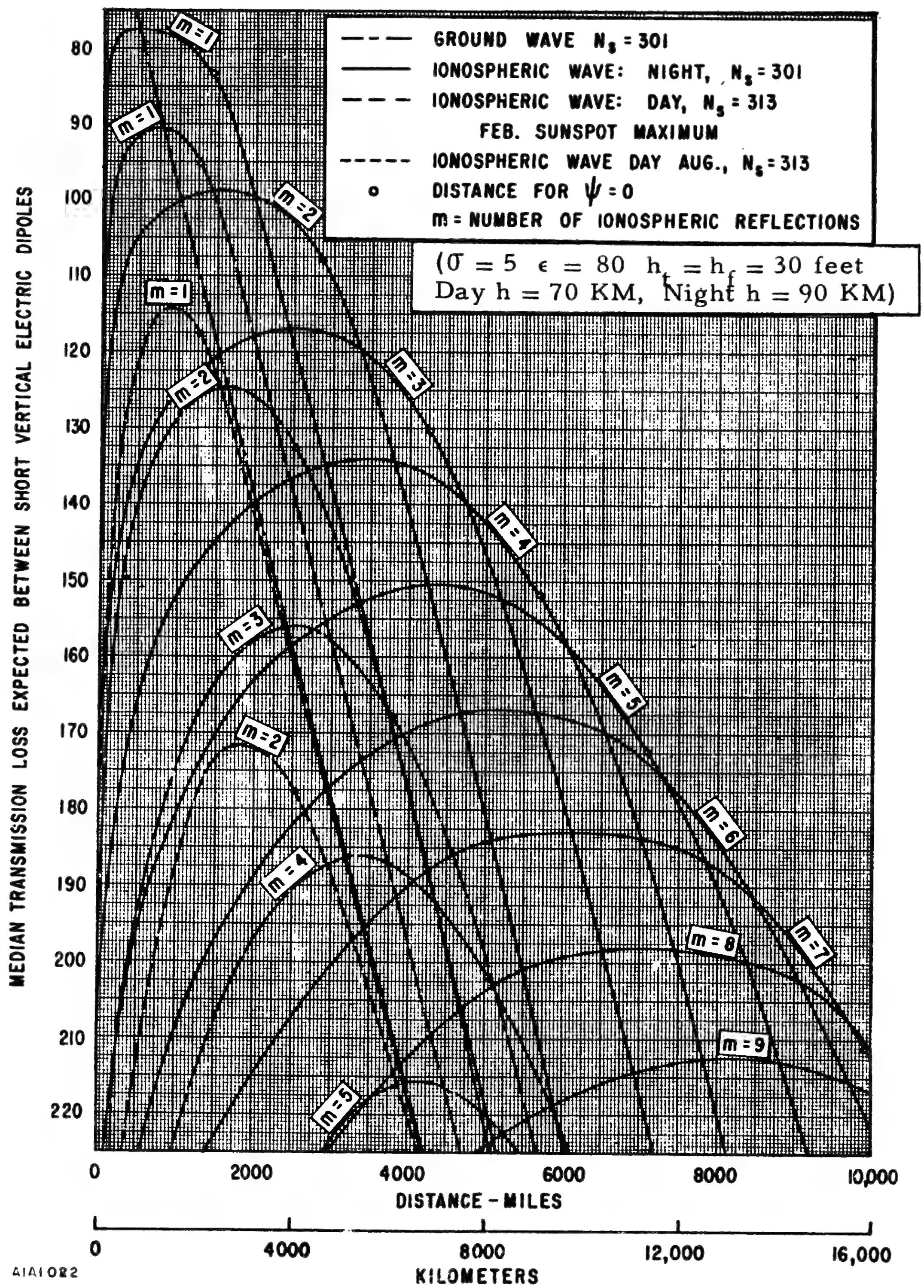


Figure 2-19. Median Transmission Loss Over Sea at 200 kHz (Typical)

where,

ϵ_N = electric field strength (μv/m) of the N^{th} mode

H = height above the earth's surface of the VLF/LF ionospheric reflecting layer (km)

P_R = power radiated from a vertical electric dipole source (kW)

R = radius of the earth (thousands of nm) = 3.44

D = distance from the dipole source (thousands of nm)

α_N = attenuation factor (dB per thousand nm) of the N^{th} mode

A convenient alternate form of this equation is:

$$\epsilon_{dB} \; 96.28 + 10 \log P_R - 20 \log H - 10 \log F - 10 \sin \frac{D}{R} - \alpha \; D$$

where ϵ, the vertical electric field strength, has the units dB relative to 1 μv/m. The attenuation factor α is a complicated function of transmitting frequency, conductivity of the ground, and ionospheric plasma and collisional frequencies. The typical variation of α with frequency for various propagation paths is shown in figure 2-20. The effect on the field strength of α-variations at a fixed transmission frequency is shown in figure 2-21. The basic α characteristic curve of figure 2-20 was used to derive figures 2-22 through 2-25. These curves show how VLF/LF field strength varies with frequency and distance. Figure 2-25 indicates the high attenuation band in the frequency range below 7 kHz, with maximum attenuation at 4 kHz. For practical purposes, the 10-30 kHz band can be considered to be frequency insensitive, with a minimum of attenuation, and is thus the most attractive for long-distance communication.

It should be noted that noise energy at VLF/LF propagates in the same manner and is subject to the same attenuations as signal energy in these spectra, and may be a major factor thousands of miles from the point of origin. Expected spheric median-levels are given in table 2-1.

Table 2-1. Worldwide Atmospheric Median Noise Levels Expected at 10 kHz for a 1 Hz Noise Envelope Bandwidth

SEASON	HOUR	NOISE GRADE				
		1	2	3	4	5
WINTER	0000-0400	-2	+4	+11	+16	+22
	0400-0800	0	+6	+13	+19	+24
	0800-1200	-3	+3	+10	+17	+23
	1200-1600	0	+10	+20	+30	+38
	1600-2000	-1	+9	+15	+22	+30
	2000-2400	0	+7	+12	+19	+23
SPRING	0000-0400	1	+7	+13	+21	+28
	0400-0800	-7	0	+8	+16	+20
	0800-1200	-9	0	+9	+17	+26
	1200-1600	+5	+15	+23	+30	+36
	1600-2000	+2	+10	+17	+23	+30
	2000-2400	+3	+10	+18	+25	+31

Table 2-1. Worldwide Atmospheric Median Noise Levels Expected at 10 kHz for a 1 Hz Noise Envelope Bandwidth (Continued)

SEASON	HOUR	NOISE GRADE				
		1	2	3	4	5
SUMMER	0000-0400	+3	+9	+14	+20	+26
	0400-0800	-1	+7	+15	+19	+22
	0800-1200	-8	+5	+18	+28	+36
	1200-1600	-7	+9	+21	+29	+37
	1600-2000	-1	+11	+19	+21	+26
	2000-2400	0	+7	+15	+21	+26
FALL	0000-0400	0	+6	+2	+17	+23
	0400-0800	-15	-6	+5	+12	+17
	0800-1200	-6	+1	+9	+16	+22
	1200-1600	-5	+3	+11	+20	+29
	1600-2000	+4	+11	+17	+23	+27
	2000-2400	+5	+12	+17	+21	+26

This data was compiled from data contained in NBS Circular 557
All values given represent the RMS noise in DB relative to 1 microvolt per meter

2.4 DISTANCE VERSUS EFFECTIVE RADIATED POWER (ERP)

To obtain curves of distance versus ERP, the variation of signal intensity with distance, the effective noise level, and the required signal-to-noise ratio (SNR) must be known. (Note that with the possible exception of low noise areas, the median noise levels are higher during night than day.) Since transmission losses are also higher during day than night, the assumption of daytime noise and transmission conditions represent the worst combination of circumstances. Signal attenuation rates will be taken from figure 2-26, which was estimated for daytime and mixed path conditions. For noise conditions, extremes in the tropics (taking noise grade = 90) and the polar regions (noise grade = 50) will be assumed. To obtain the required SNR, the type of service and the allowable error rate must be assumed. Two cases are considered: Aural Morse code at 12 wpm (514 Hz receiver bandwidth); and frequency shift keying (FSK) teletype (TTY) (± 25 Hz) at 60 wpm (120 Hz if, and 70 Hz post discriminator bandwidth), both at one percent character error rates, (10^{-3} CER desired normally for FSK). For these two cases, the root mean square (rms) carrier to rms noise (C/N_{1kHz}) in a 1 kHz effective noise power bandwidth will be taken as -2 dB and +8 dB, respectively. Finally, allowance must be made for statistical variations in signal and noise levels about their median values. We shall adopt the curve of variability allowance, T_X, versus frequency given by Watt and Plush which shows a roughly constant value of 10 dB between 10 kHz and 30 kHz for 90 percent of all hours.

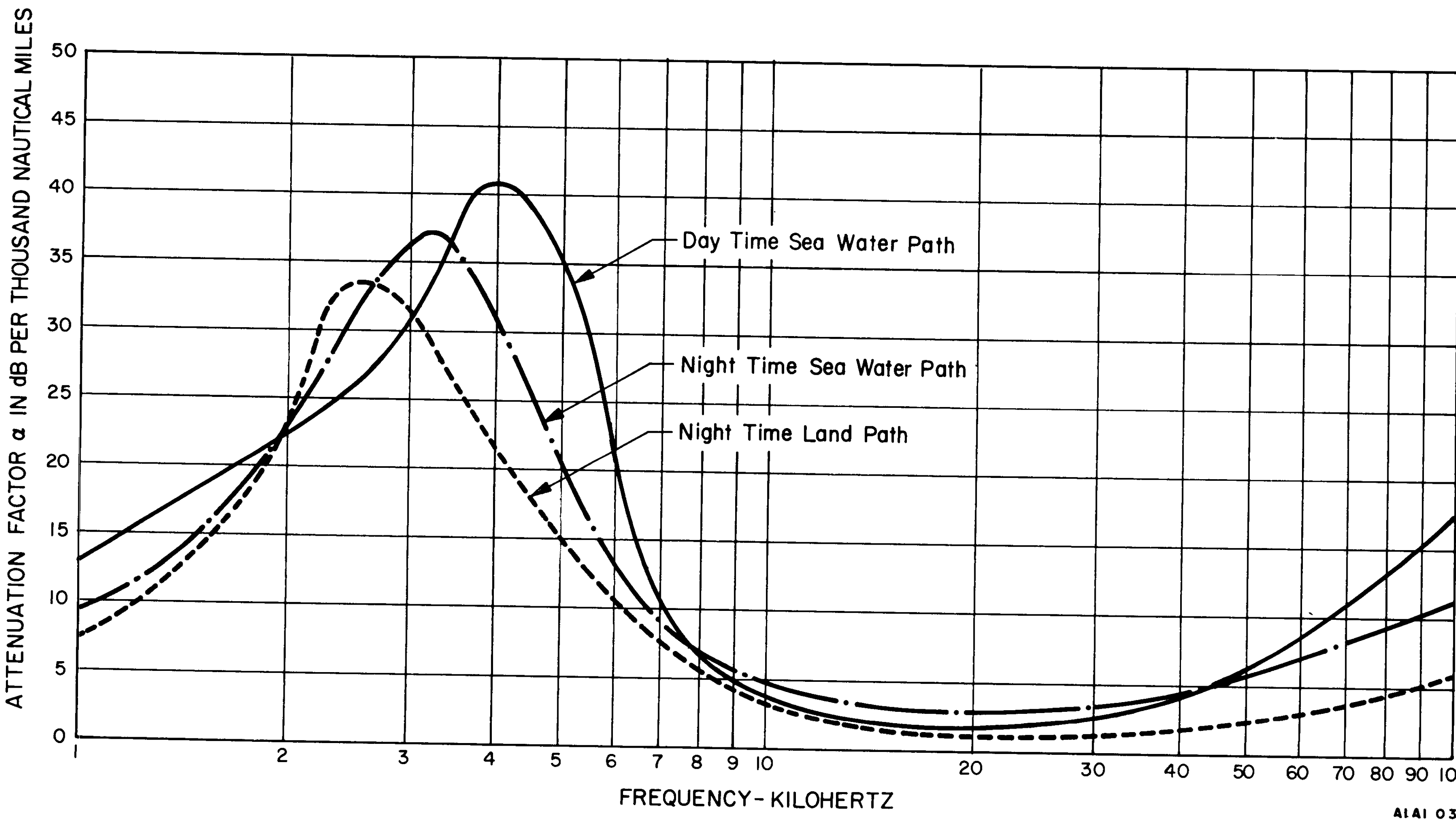


Figure 2-20. Variation of Attenuation Factor a With Frequency for Various Propagation Paths

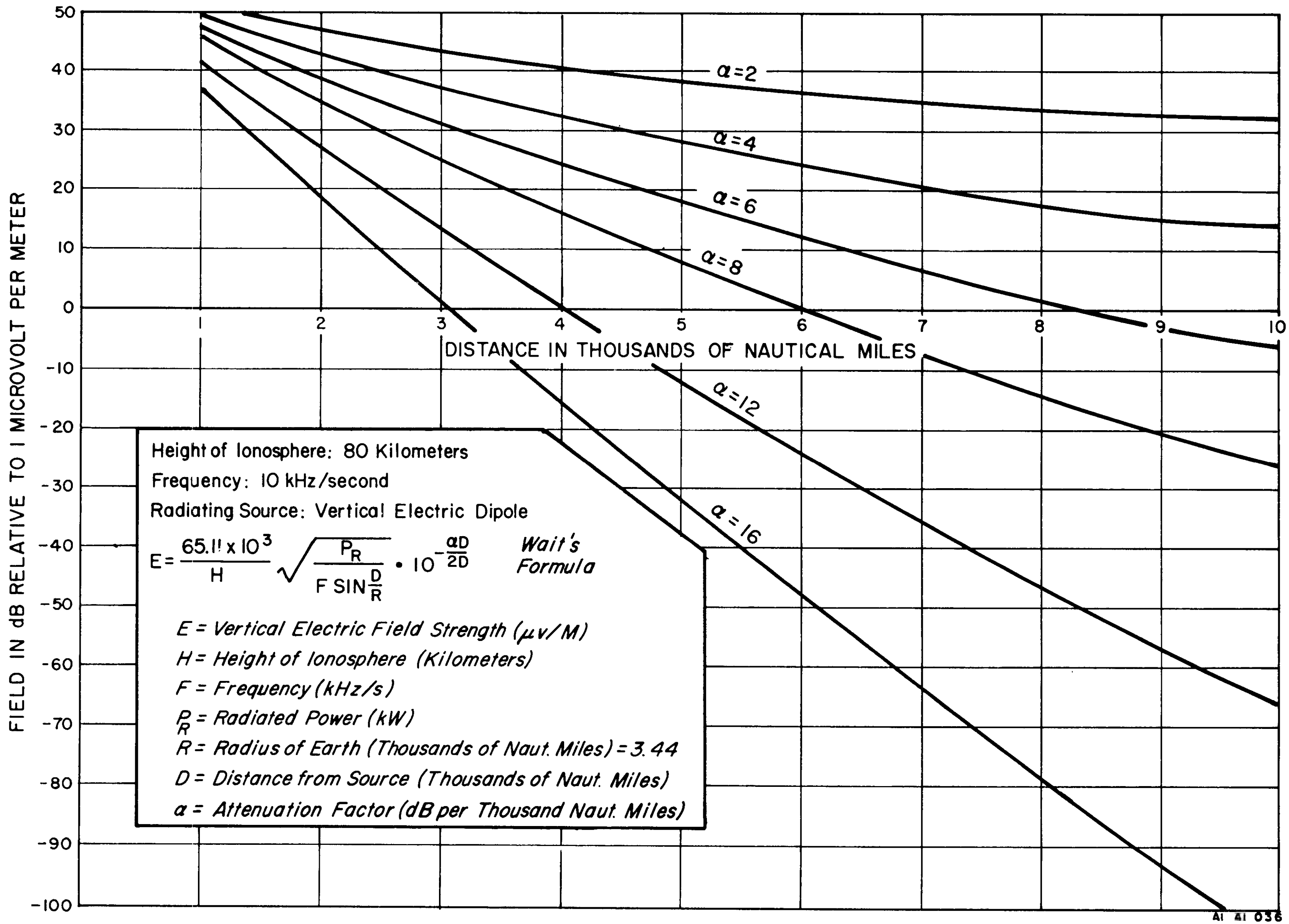


Figure 2-21. Vertical Electric Field Strength as a Function of Distance From a 1 kW Radiating Source for Various Values of Attenuation Factor

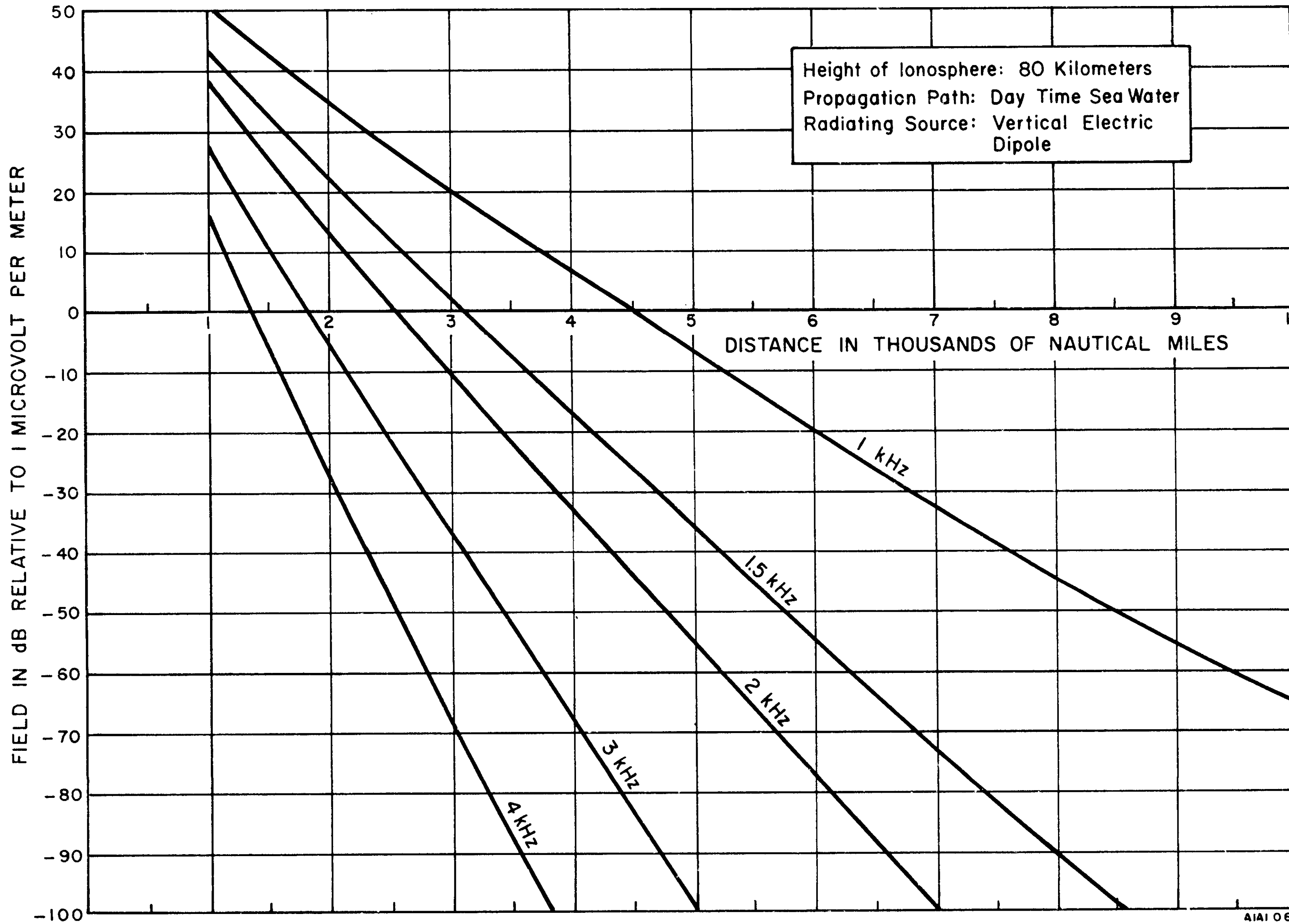


Figure 2-22. Variation of the Vertical Electrical Field Strength With Distance From a 1 kW Radiating Source at 1 to 4 kHz

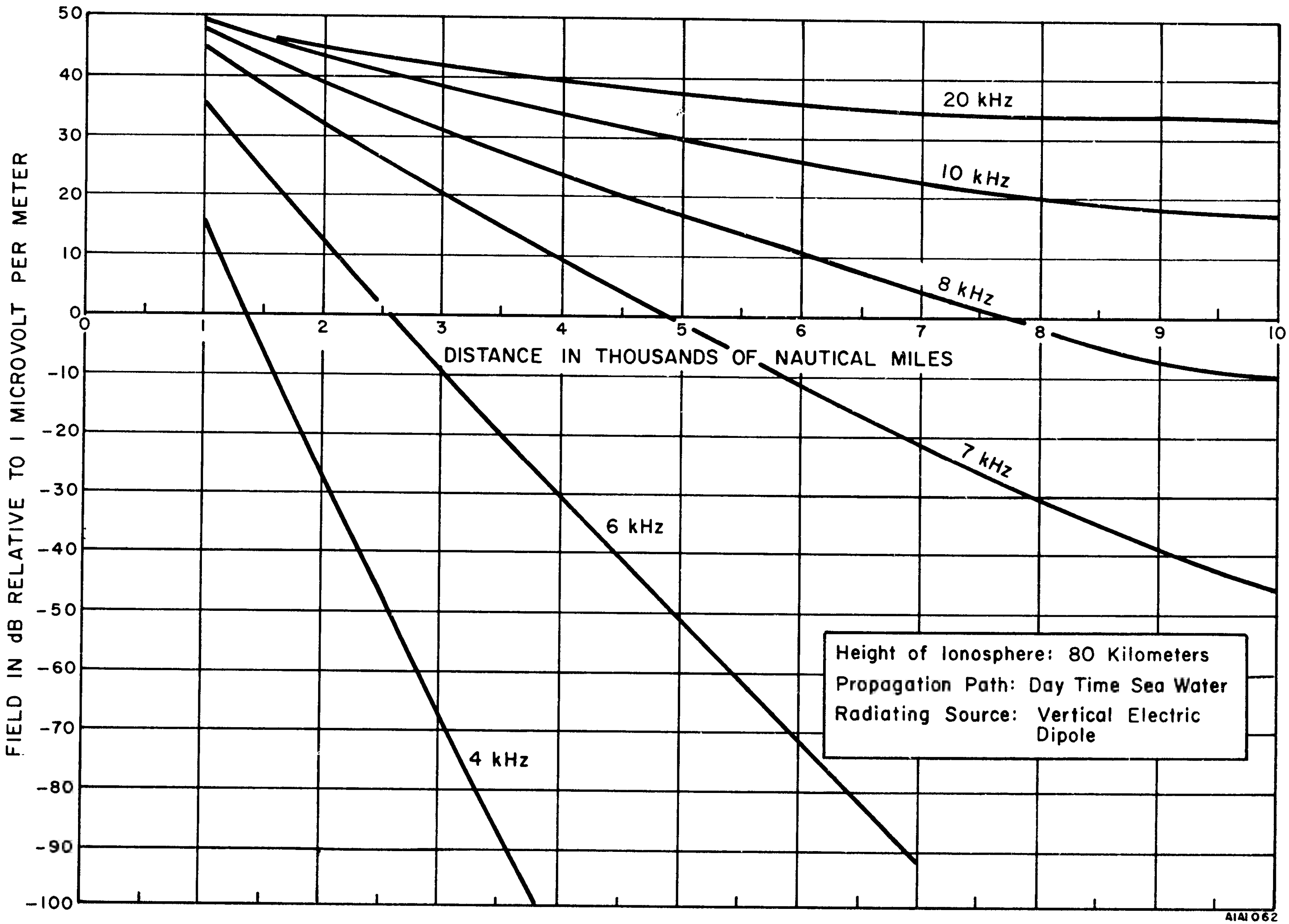


Figure 2-23. Variation of Vertical Electric Field Strength With Distance From a 1 kW Radiating Source at 4 to 20 kHz

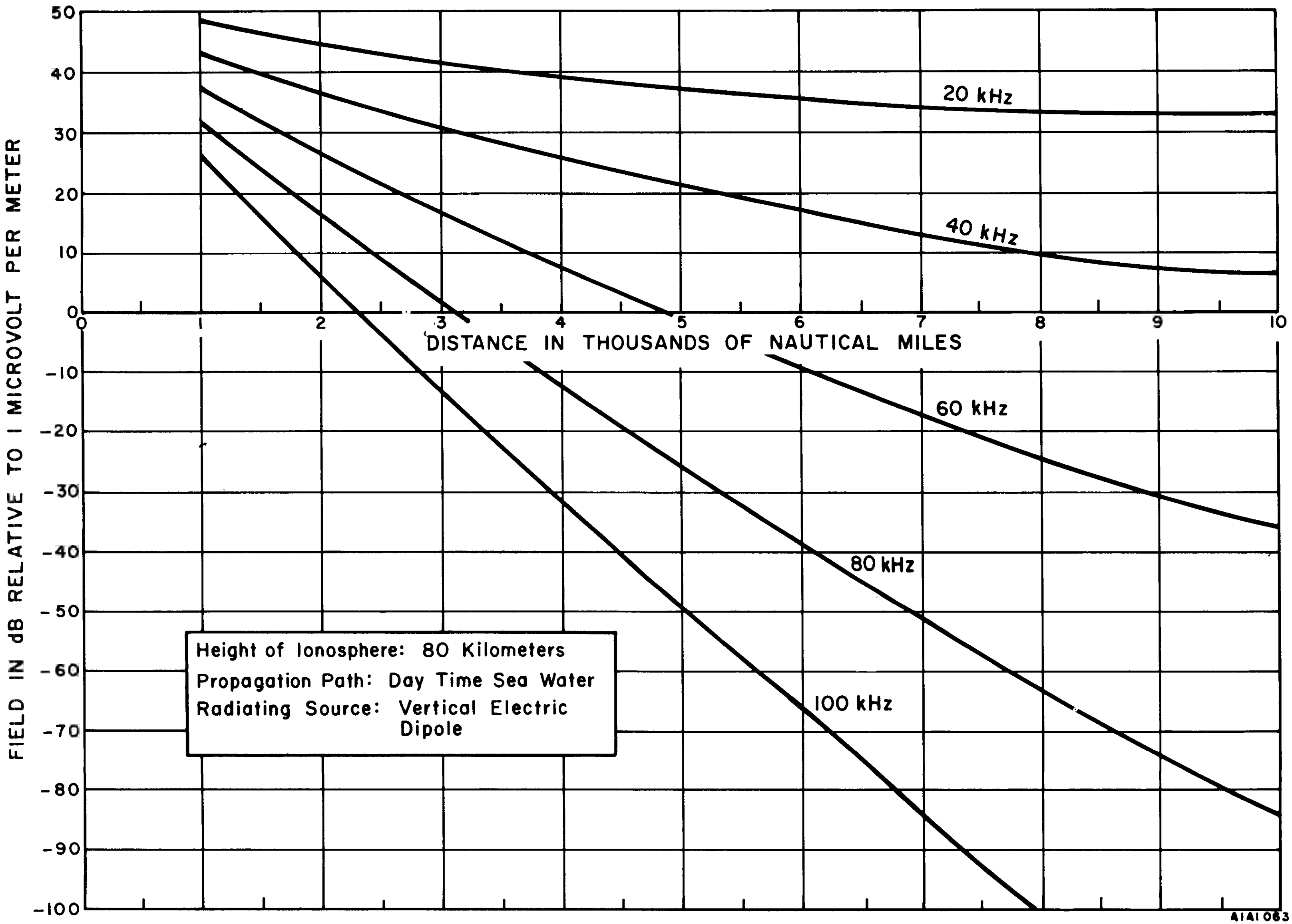


Figure 2-24. Variation of Vertical Electric Field Strength With Distance From a 1 kW Radiating Source at 20 to 100 kHz

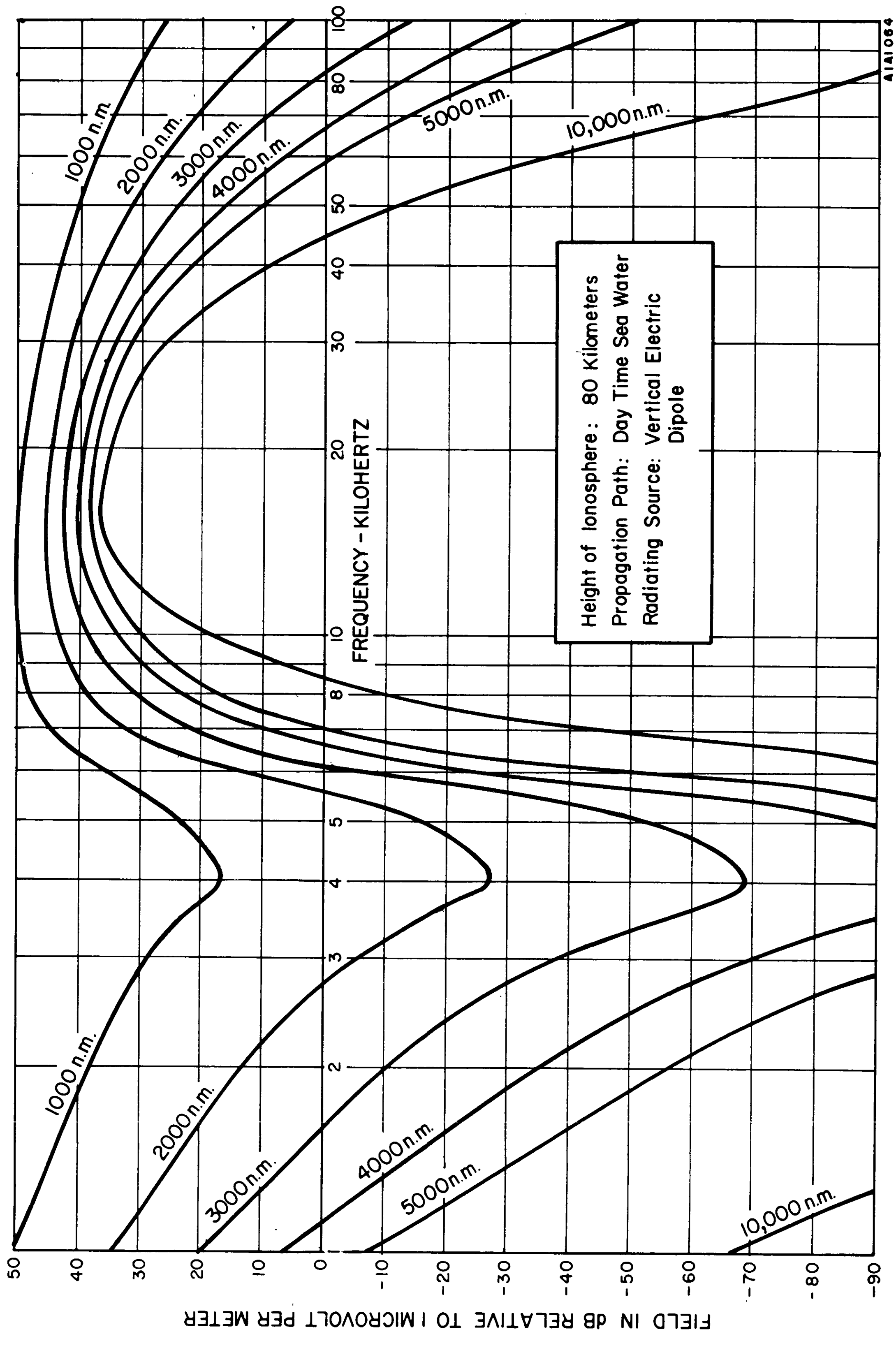


Figure 2-25. Variation of Vertical Electric Field Strength With Frequency at Various Distances From a 1 kW Radiating Source

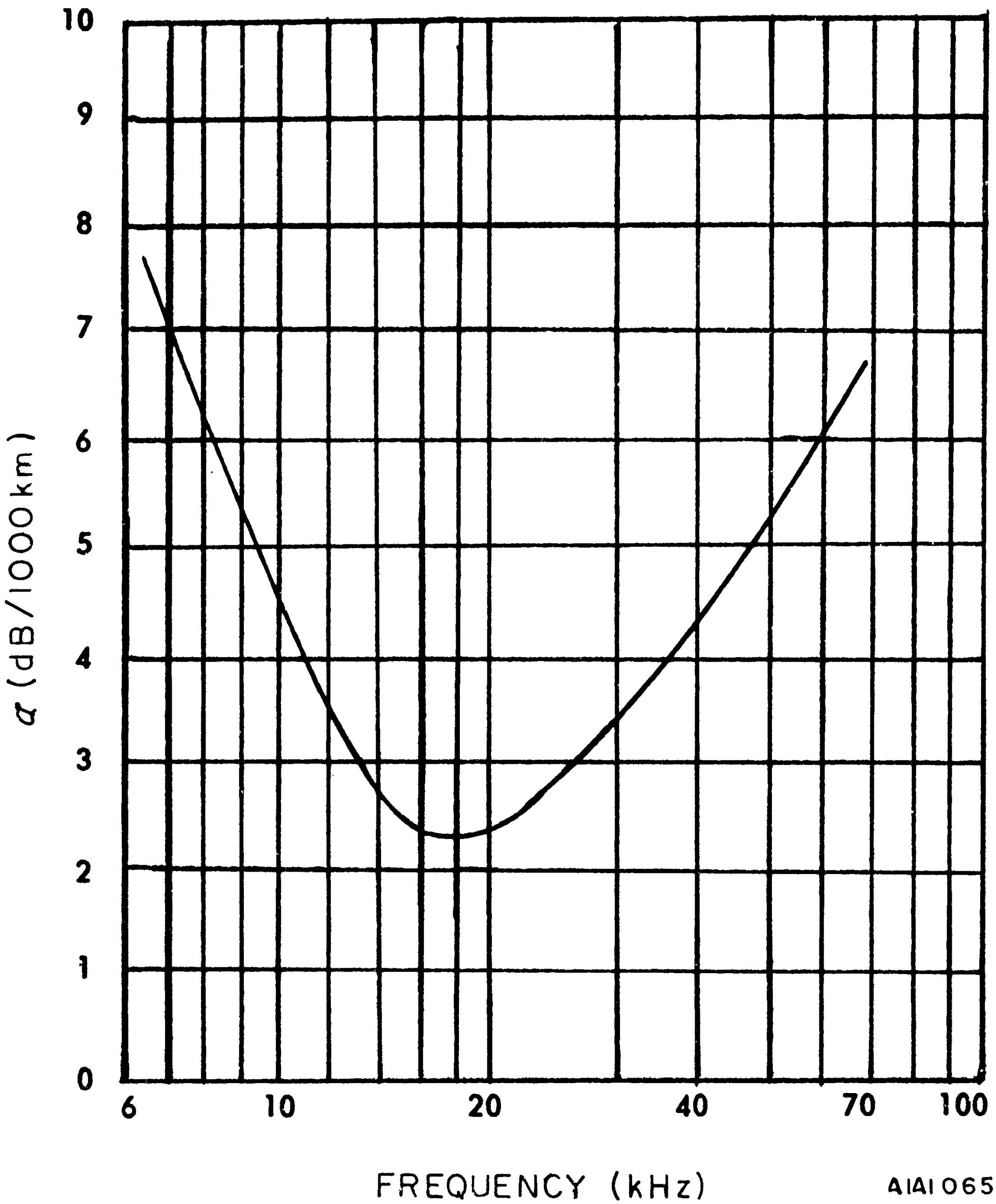


Figure 2-26. Average Attenuation Rate for Daytime Conditions and a Mixed Path (20% Land, 80% Sea)

To simplify the presentation of results, only distances beyond 2000 km are considered. (This limitation is justified by the fact that any conventional VLF system which will provide service beyond 10,000 km can also serve locations within 2000 km.) Calculations are based on equations (2-3) and (2-4) of the paper by Watt and Plush (see Appendix B-2 item 33.) For ranges in excess of 2000 km, the received vertical electric field in dB relative to one μv/m is given by

$$E = K + P_r - 10 \log_{10} f_{kHz} - 10 \log_{10} [a \sin (d/a)] - \alpha d/1000 \qquad (2\text{-}3)$$

where:

K = 97.5 for day paths; 94.8 for night paths
P_r = radiated power in dB relative to 1 kW (vert. antenna)
f_{kHz} = frequency in kHz
a = earth's radius = 6400 km
d = path distance in km
α = attenuation in dB per 1000 km

The radiated power in dB relative to 1 kW for a given type and quality of service is given by

$$P_r = -E_1 + E_{nm} + C/N_{ikHz} + T_X \qquad (2\text{-}4)$$

where:

E_1 = received field in dB relative to 1 μv/m for 1 kW radiated.
E_{nm} = median rms noise field in dB relative to 1 μv/m for a 1 kHz bandwidth.
$C/N_{1\ kHz}$ = required rms carrier to rms noise in a 1 kHz bandwidth (-2 dB for 12 wpm Morse, 8 dB for 60 wpm FSK)
T_X = variability factor = 10 dB.

E_1 can be eliminated from equation (2-4) by putting P_r = 0 dB in equation (2-3) and substituting in equation (2-4). The resulting expression for the effective radiated power (ERP) versus distance is:

$$P_r = -97.5 + 10 \log_{10} f_{kHz} + 10 \log_{10} \left[6400 \sin \frac{d_{km}}{6400} \right] + \frac{\alpha d_{km}}{1000} + E_{nm} + C/N_{1\ kHz} + T_X \qquad (2\text{-}5)$$

From examination of figure 2-26 and the frequency variation of the other variables, it is seen that the effective radiated power is controlled primarily by the attenuation rate α. Since α reaches a minimum at about 18 kHz, this will be the approximate optimum frequency. For comparison, curves of ERP for 10 kHz and 30 kHz are calculated. The daytime values of E_{nm} taken from CCIR Report No. 65 for noise grades 50 and 90 together with values of α from figure 2-26 are tabulated in table 2-2 for the three frequencies.

Substituting these quantities and carrying out the operations indicated in equation (2-5) one obtains the effective radiated power as a function of distance. Families of curves parametric in frequency are shown in figures 2-27 and 2-28 for tropical receiving locations (maximum noise grade = 90) and polar receiving locations (maximum noise grade = 50) respectively.

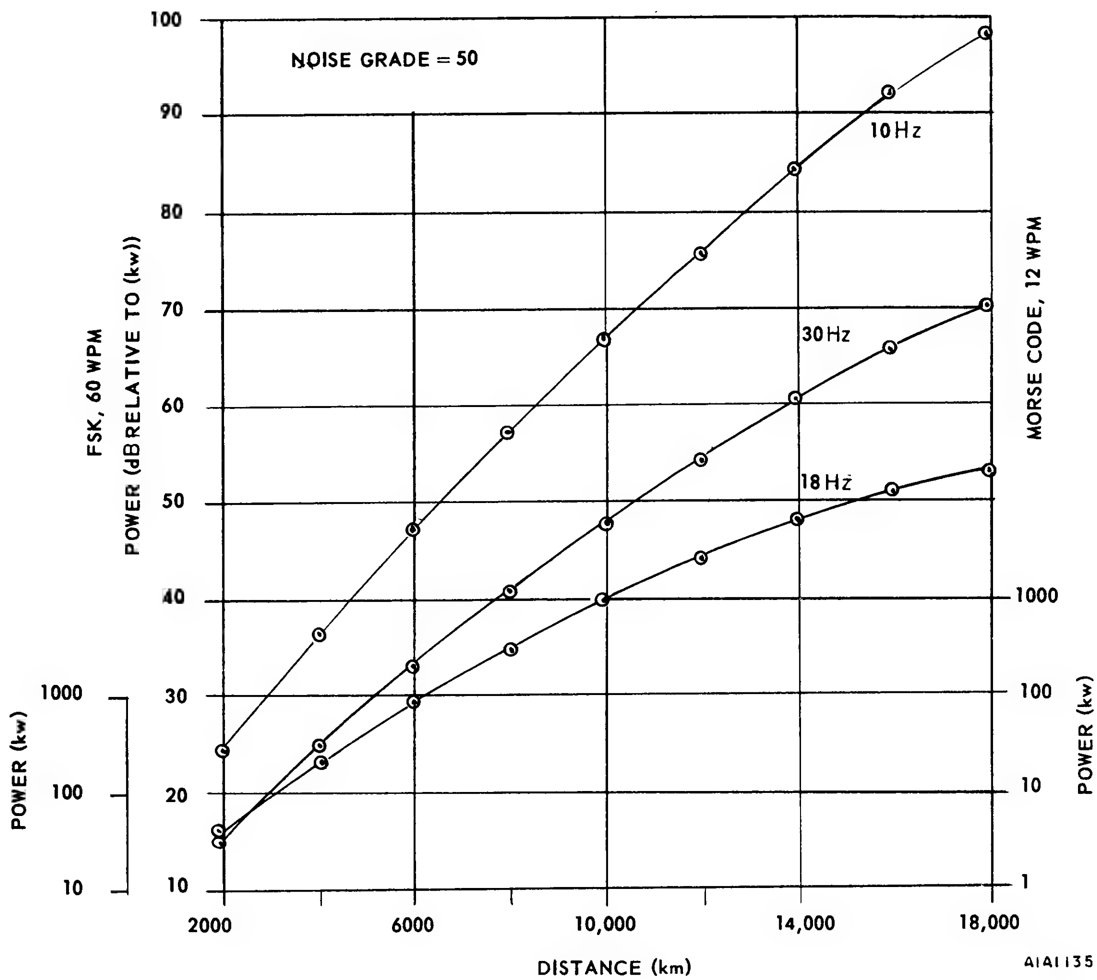


Figure 2-27. Effective Radiated Power Required for Tropical Receiving Areas

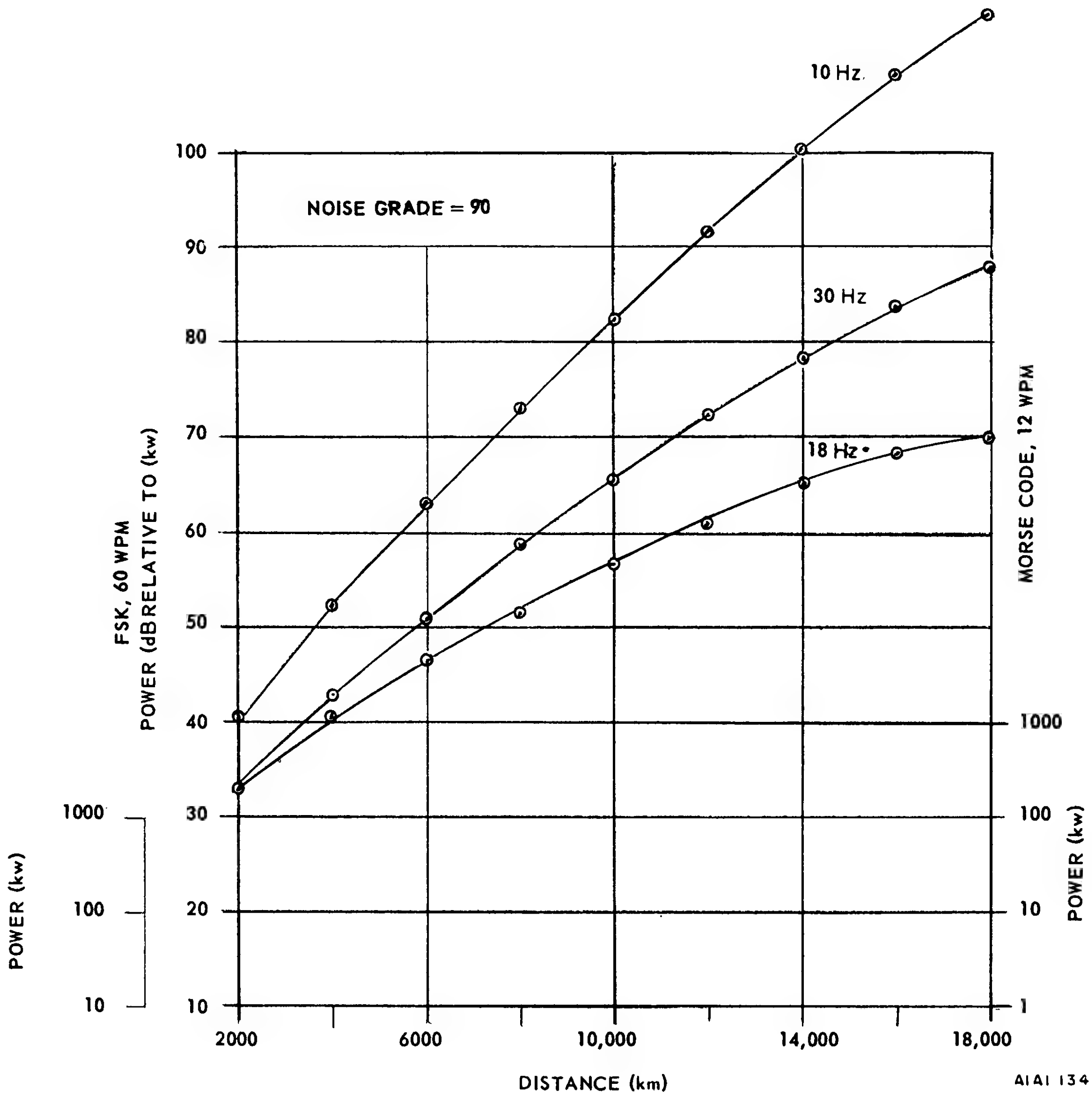


Figure 2-28. Effective Radiated Power Required for Polar Receiving Areas

Table 2-2. Median RMS Noise Field (E_{nm}) for Noise Grades 50 and 90

FREQUENCY (1 kHz BANDWIDTH)	10 kHz	18 kHz	30 kHz
E_{nm} (Daytime) Noise grade = 50 Noise grade = 90	 52 dB 68 dB	 46 dB 63 dB	 40 dB 58 dB
α (dB/1000 km)	4.6	2.3	3.4

It is immediately seen that even for Morse code at 12 wpm, 100 kW will reach only 2000 km for the worst tropical receiving conditions. In polar areas during high noise a distance of about 6000 km is possible. To obtain reliable transmission over the full 18,000 km at the assumed error rate of 1 percent would require about 40 dB of improvement in SNR in the tropics and 23 dB in polar areas. This improvement might be obtained partly by raising the ERP by 10 dB (to 1 megawatt). However, this leaves 13 to 30 dB to be found elsewhere. The use of broadband noise suppression circuits, directive antennas, and other receiver circuit improvements will increase the coverage area.

2.5 NOISE AND INTERFERENCE

The characteristics of the ionosphere modify the phase, amplitude, and polarization of the sky wave. The ionosphere is a complex medium with variable characteristics which cause variations in the propagation characteristics of the sky wave. The sky wave, upon reflection from the ionosphere, becomes elliptically polarized due to the earth's magnetic field and the ionized media. The phase of the sky wave is retarded with respect to the ground wave, both by the reflection from the ionosphere and the path length. Since the total propagated field is the vector sum of the ground wave and the sky wave, variations of the ionosphere will cause variations in the propagated field.

The ionization and height of the lower ionosphere depend on radiation from the sun and will have diurnal and seasonal variations. In addition, sunspots and magnetic storms cause changes in the properties of the ionosphere. Thus, propagation conditions vary diurnally and seasonally with changes superimposed at times of sunspot activity and magnetic disturbances.

o Diurnal Variations. The VLF and LF sky wave is quite stable with time especially during the hours of daylight. In general, the reflection coefficients and height of the ionosphere are greater during the night. Rapid changes occur in the ionosphere at sunrise and sunset hours causing rapid changes in the signal between the day and night stable conditions.

o Seasonal Variations. Seasonal variations in the composite field are apparent in the magnitude and regularity of the diurnal variations. During the summer, the diurnal variation is regular; in winter the amplitude is higher, but less regular.

o Other Effects. Magnetic storms and solar flares cause the ionization to increase and the height of the lower ionosphere to decrease thus affecting the atmospheric noise, (a decrease below 10 kHz, and an increase from 20 - 40 kHz and possibly from 10 - 200 kHz). In general, magnetic storms do not affect daylight paths, however, paths in darkness suffer increased attenuation. Solar flares generally increase the attenuation for frequencies below 10 kHz and decrease the attenuation for those between 10 kHz and 30 kHz. In the LF spectrum, rapid and deep fading usually occur at night. During the summer, solar flares cause an overall decrease in attenuation. In winter, on short paths, attenuation usually shows a sudden increase followed by gradual decrease to a minimum and then a gradual increase to the normal value. Long paths (2000 km) generally show a decrease in attenuation during the occurrence of solar flares.

2.5.1 Noise Classification

a. Atmospheric. At frequencies of 3 to 3000 kHz atmospheric noise, (spherics) is the limiting noise factor a greater percentage of the time than at medium and high frequencies. Receiver noise is negligible compared with atmospheric noise at these frequencies. Atmospheric noise at these frequencies is largely impulsive since the source is lightning and consists of transients separated by periods of relatively low noise. The interfering effect of this type of noise to a system is in general not the same as that of thermal noise of equal power. The degradation of system performance by noise involves design parameters of the particular system such as modulation techniques and the complex transfer characteristic of the receiver. Frequently, receiver designs incorporate clipping or "noise elimination" circuits which are quite effective in minimizing the effect of impulsive noise. Receiver performance, however, is usually measured in terms of signal to random noise ratio. Most noise measurements are made with narrow band equipment and assume an equivalence to random noise. In general, these parameters alone are not sufficient to predict the performance of a particular receiving system in the presence of spherics, especially at lower frequencies where higher noise levels are generally associated with large discrete pulses.

Amplitude-time or probability distributions of the noise-envelope voltage provide information on the short-term variations of the noise and such measurements have been made by a number of investigators. However, no two samples of noise will have identical amplitude-time relationships and because of the complexity of the equipment involved and the number of personnel required to make such measurements, it has not been practicable to observe the amplitude-time characteristics continuously or over extended time intervals.

Numerous attempts have been made to evolve a mathematical model for the distribution of noise at various frequencies, but most of these are extremely complex, and it appears that no simple mathematical representation will fit all conditions. A graphical method of approximating the complete distribution by use of the measured power, voltage, and logarithm of the voltage has been developed, but the resulting distribution is valid only for the bandwidth in which the momentums were measured.

The presently available distribution measurements are too few, and proposed mathematical or graphical analyses insufficiently developed, to be used in developing a performance standard applicable on a worldwide basis. At present, they are useful in estimating noise effects on system performance. It appears essential to establish performance of the particular system in terms of existing noise predictions, which are in terms of noise power. Atmospheric noise which passes into outer space and returns is known as the whistler phenomenon.

b. Man-Made. Under this classification are radiations from power lines, electrical machinery, ignition systems, etc. Man-made noise should generally be below the atmospheric level most of the time at VLF and LF, except perhaps in polar regions where spherics may be very low.

c. Cosmic. This thermal-type noise, originating in the sun and other celestial bodies, has been recorded at LF under certain conditions. However, it may usually be neglected at VLF and LF because of the shielding effect of the ionosphere to radiation at these frequencies.

2.5.2 Variations of Noise

a. Diurnal. Atmospheric noise (spherics) at VLF and LF is usually lowest in the daytime. At night the noise is propagated from storms at great distances by the ionosphere; during the day there is a reduction in noise level because ionospheric absorption lowers the contribution of the distant storms. However, local storms tend to produce an increase in noise level during the afternoon that may even exceed the nighttime levels during the hours of peak activity.

(1) The median diurnal range of noise power may vary from about 5 to 10 dB at 10 kHz to about 40 dB in the upper part of the LF band, depending somewhat upon geographical location. Variations of as much as 60 to 70 dB have been observed on individual days in the LF band. It is usually assumed that peak thunderstorm activity occurs in the afternoon (two to three hours after local noon) and while this is generally true considering the average activity for the whole world, in many areas peak activity may occur in the late evening or morning hours. It is possible therefore to have a relatively low diurnal variation in noise level for certain areas due to the "leveling-out" effect caused by nearby activity during the morning hours.

(2) A thunderstorm near a receiving point is likely to cause a sudden increase in noise power of 20 to 40 dB, but the degree to which local activity will affect the noise level at a receiving site depends on many factors such as the number of thunderstorm cells, amount of cloud development, rate of movement, etc. In polar regions diurnal variations are normally small with midnight and midday values apt to be about the same.

(3) Diurnal changes in man-made noise may be related to power consumption, nearby traffic, degree of darkness, operating periods of certain machinery or appliances, and other factors. Since diurnal variation depends on the nature of the sources at a particular site, no general statement can be made as to the type or amount of this variation.

b. Seasonal. The main thunderstorm centers tend to shift above and below the equator from summer to winter. During the northern hemisphere summer the tropical storm centers shift northward and there is an increase in temperate-latitude activity, e.g., in the Rocky Mountain region of the United States. This tends to increase the noise levels (day and night) for north temperate latitudes in the summer. The largest seasonal changes can be expected near the center of large temperate zone land masses, where local activity may be relatively high in summer but in winter the nearest storms may be several hundred to a few thousand miles away, with relatively poor propagation over the extensive land mass as compared to a coastal or island location where the noise is propagated chiefly over sea.

o In general, seasonal changes in noise are greater at LF than at VLF. The noise is usually higher at temperate and tropical latitudes in the local summer (or wet) season than in the winter (or dry) season; however, in certain areas seasonal variation can be quite small.

c. Geographical. As a rough approximation, spherics decrease from the equator toward the poles, principally because many of the major noise sources are in the tropics. Receiving sites in or near the main tropical storm centers can expect high noise levels, while sites at great distances from these centers will have lower noise levels. A location near a storm-triggering mountain range will usually have higher average noise than a station a few hundred miles away on a plain. Poorer propagation over land than over sea tends to produce lower noise levels in areas near the center of large land masses (in the absence of local activity). Island areas at great distances from any major storm center (e.g., Hawaii) are likely to have relatively small day-to-day and seasonal changes in noise levels. Among the major thunderstorm (and radio noise) producing areas of the world are central and northern South America, central and southern Africa, southeast Asia and Indonesia, central and southern United States and Central America. The areas contributing the major part of the noise at any particular receiving site will vary considerably with the seasons.

(1) At any particular receiving site certain noise sources will tend to be dominant, and therefore noise arriving at the site from various directions will frequently show rather large average differences in amplitude. Some improvement in signal-to-noise ratio may therefore be obtained when directional antennas can be used.

(2) Figures 2-29 through 2-33 illustrate some observed diurnal and seasonal VLF/LF noise characteristics for stations in various part of the world.

d. Other Effects. While the effect of long period changes in sunspot activity on radio noise is uncertain, solar flares and sudden ionospheric disturbances (SID's) have been shown to correlate with some observed changes in noise. In general, it appears that a SID may have the following effect at VLF and LF: a decrease in noise spheric level below 10 kHz and an increase in atmospheric noise from 20 to 40 kHz and possibly from 10 to 200 kHz. These effects may occur over periods ranging from less than an hour to several days. In polar regions there may be virtual blackouts of communications caused by spherics during periods of unusual solar disturbances.

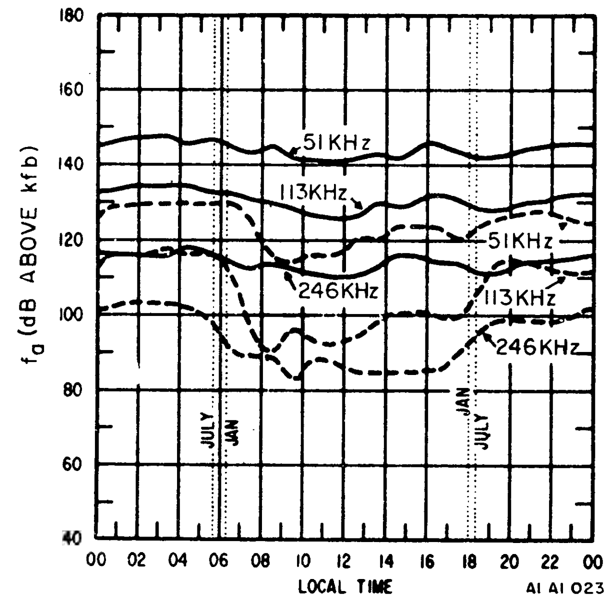


Figure 2-29. Median Observed Noise Power at Balboa, C.Z.

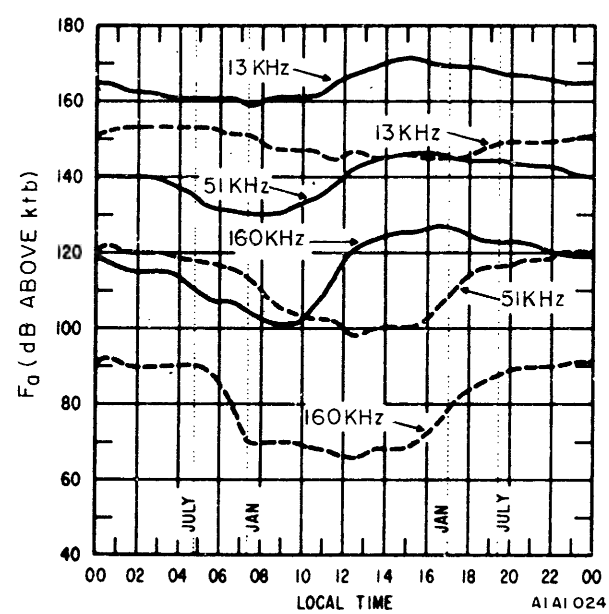


Figure 2-30. Median Observed Noise Power at Boulder, Colorado

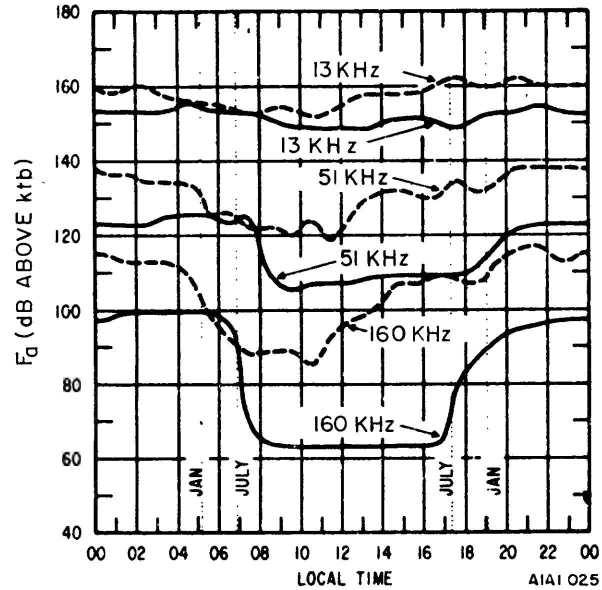


Figure 2-31. Median Observed Noise Power at Cook, Australia

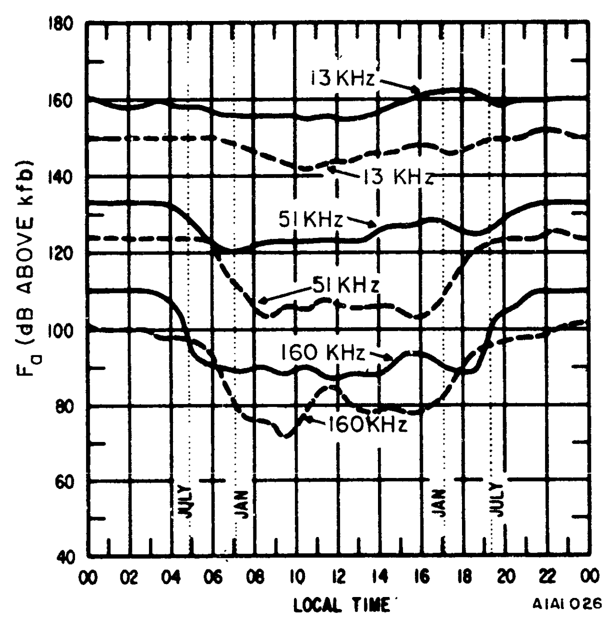


Figure 2-32. Median Observed Noise Power at Ohira, Japan

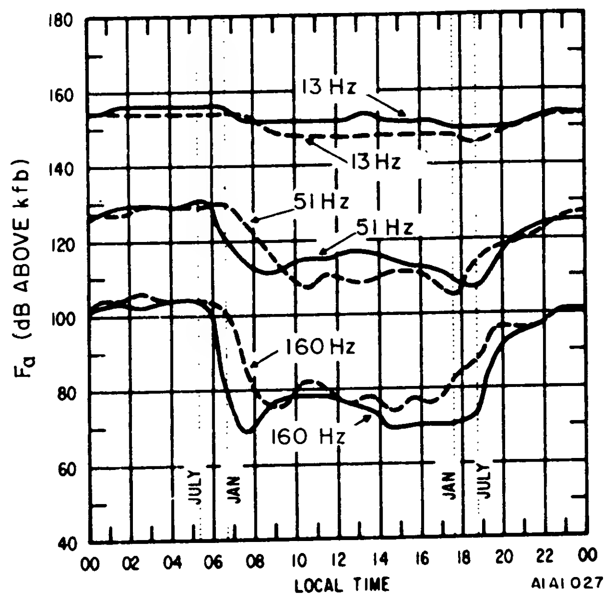


Figure 2-33. Median Observed Noise Power at Kehaha, (Kauai) Hawaii

(1) There is evidence that spherics reach peak intensity at around 10 - 20 kHz and then diminishes from about 8 kHz to 2 to 5 kHz, but this is probably true only of spherics propagated over long distances.

(2) Whistlers. Some VLF energy leaks through the ionosphere into outer space. There is a special kind of interference which also passes through outer space. This interference is peculiar to frequencies between about 300 Hz and 35 kHz and is known as a "whistler". A whistler is a virtually constant amplitude signal of decreasing frequency with the square of time. On a receiver with BFO the signal tone starts at a high pitch, drops, and then rises again. Whistlers are generated by lightning. Lightning is an impulse which propagates energy at all frequencies up to about 30 MHz with power density which is essentially constant.

The reaction of the lightning energy with free electrons in the ionosphere causes some energy to travel out from earth along a duct bounded by the lines of force in the magnetosphere. Since the duct is a form of waveguide the different frequency components travel at different velocities. The lower frequencies are slowest. At the other end of the duct the signal appears as a tone of decreasing frequency. The duct is a region between the earth's magnetic field lines and terminates at its conjugate earth point. The conjugate point for the duct is the point in the opposite hemisphere with the same numerical magnetic latitude. Whistlers normally are of short duration, lasting a few tenths of a second.

The first ducting results in a short whistler. Some energy is reflected back to the hemisphere of origin resulting in a long whistler. Frequently the losses along this duct are negligible and many successive reflections can occur resulting in whistlers lasting several seconds. The whistler ducts pass out into space from 4,000 miles to 20,000 miles from the earth's surface.

(3) Rather large-scale and persistent effects on radio noise have been observed in connection with high-altitude nuclear explosions. The effect appears to be chiefly one of greatly increased absorption, with LF affected to a greater degree and over a longer period of time than VLF.

(4) Several short-period and localized effects on noise at receiving sites exist in addition to those related to thunderstorm lightning discharges. Charges carried on precipitation particles (precipitation static) may result in large increases in the noise level for brief periods. The passage of a highly charged cloud over an antenna may cause a similar effect through corona discharge even when no precipitation is occurring. Blowing dust and sand may also produce relatively high levels of interference and a significant source of noise in polar regions is the "snow static" which occurs when surface snow and ice accumulations are moved to a considerable distance above the surface by high winds. This effect is more pronounced at a very low temperature but may also be observed at times in temperate latitudes.

2.5.3 Interference

The principal source of interference at VLF and LF is atmospheric noise (spherics). Spherics are produced by lightning discharges and may have energy levels of the order of hundreds of thousands of joules. Such high energies are well above the powers radiated by the highest powered radio stations.

Individual spheric signals are highly damped pulses with decay-times of the order of 100 microseconds. The spheric pulse frequency-spectrum is very complex, with the spectrum of individual pulses varying considerably. The return stroke (main discharge) of the lightning stroke is preceded by a number of small leaders which have relatively low energies compared with the return stroke. These low-velocity leaders may take several hundred microseconds to reach the ground. For storms at great distances these leaders contribute little to the background noise level but can be important with local storms.

The frequency spectrum of a lightning discharge as recorded by a receiver will depend on the distance to the source of the spheric, the characteristics of the path between the source and receiver, and the response of the receiver. Figure 2-34 shows the frequency spectrum of the radiation component equivalent field intensity at a distance of one mile. It is seen that the signal peaks near 5 kHz, with a decay-rate slope between the reciprocal of the frequency and the reciprocal of the frequency squared. As the signal is propagated, the lower frequencies suffer greater attenuation which shifts the spectrum higher in frequency. The peak of the response of spherics which have traveled large distances is in the vicinity of 8 to 10 kHz. Since the attenuation increases with frequency above the frequency of maximum response, the slope of the curve in the higher frequencies becomes steeper as the range to the spherics is increased.

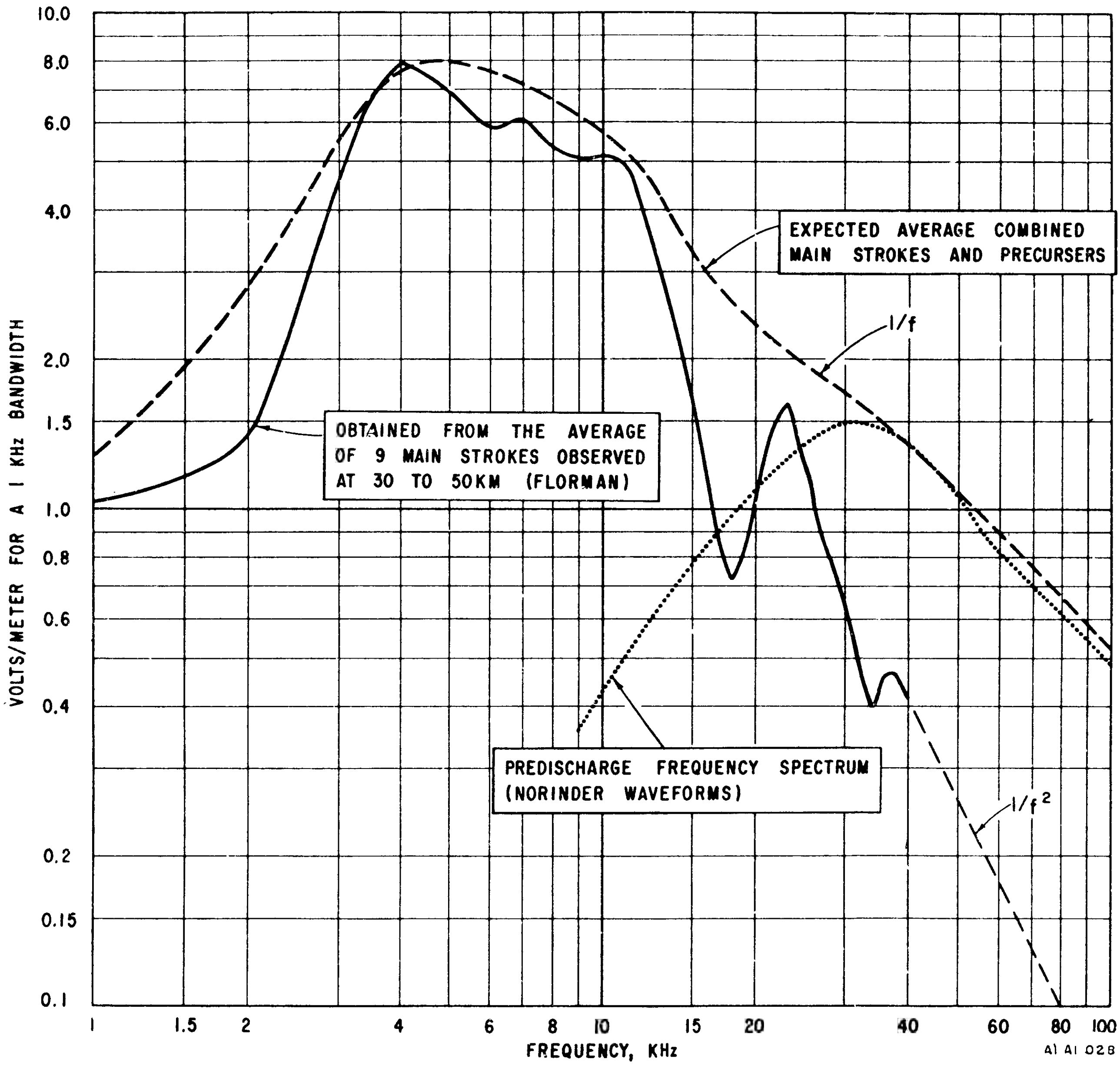


Figure 2-34. Frequency Spectrum of the Radiation Component Equivalent Field Intensity at a Distance of One Mile

Storms producing spherics are continually in progress somewhere on the earth. A typical world distribution of noise is shown in figure 2-35. The value of Fa is the expected noise power available from a short, vertical, grounded, loss-free antenna.

The effective noise figure (Fa) is determined from the hourly median value of the available noise power. It can be seen that maximum noise intensity occurs in the tropical regions over land masses and that there are very low levels in the arctic regions.

Spherics have a seasonal variation associated with summer thunderstorm activity and also exhibit diurnal variation. Noise maps of the type of figure 2-35 provide noise grades covering the calendar quarters of the year in four-hour time-blocks. The noise grades, derived from noise values measured on a world-wide network of receiving stations, are expressed in effective noise figure at 1.0 MHz.

To extend this data to other frequencies, curves such as shown in figure 2-36 are used. Two such families of curves are required to cover all the seasons in four-hour time-blocks. Procedures for determining noise values for any period are covered in paragraph 2.5.4.

At LF and VLF, spheric energy is very high as previously mentioned, peaking in the low end of the VLF band. Also at these frequencies the transmission losses are low. These two factors combine to produce a high background noise level in this frequency range. During local quiescent periods the noise arriving from great distances has a time-amplitude distribution similar to that of white noise and gives a characteristic hissing sound from the receiver. When local storms (within 1000 miles) are in progress, the time-amplitude distribution is considerably different with large bursts of noise being present.

Local storms can produce spherics of sufficient amplitude (up to hundreds of volts per meter) to saturate a receiver. A considerable loss of communication time can result from receiver recovery time after a spheric overload. Narrow band receivers using high-Q circuits may have a "ringing time" of milliseconds after shock excitation by a high-level signal. Thus, while the spheric decays in tenths of a millisecond or less, oscillations in the receiver may block the receiver for several milliseconds.

To reduce these effects, the following methods are sometimes introduced:

o Antenna bandwidth is increased to a point where it reflects the shape and duration of the disturbing pulse. As a result, all amplitudes (signal and noise) in the antenna are reduced because of the increased damping of the circuits. This can be done because in the VLF/LF band there is generally margin of 100 to 120 dB between spherics and thermal noise.

o At the wideband output circuit, the high amplitude of the disturbing pulse is limited to the peak of the signal to remove all pulse energy greater than the signal amplitude.

o The "method of cancellation" is used by applying to signal-plus-noise a controlled amount of the same noise 180 degrees out of phase.

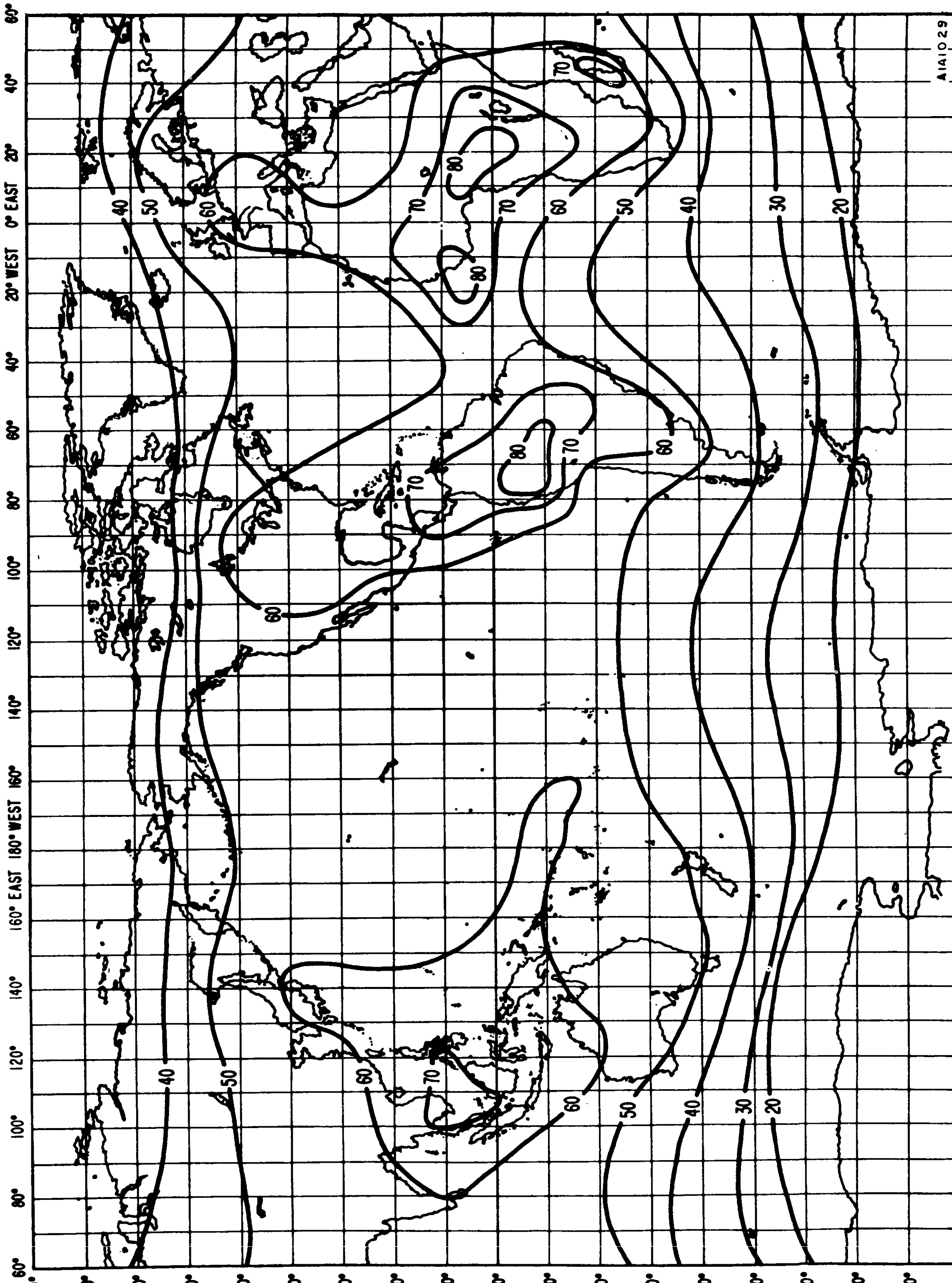


Figure 2-35. Expected Values of Radio Noise in dB Above KTB at 1 MHz From 0400-0800 Hours for September, October, and November

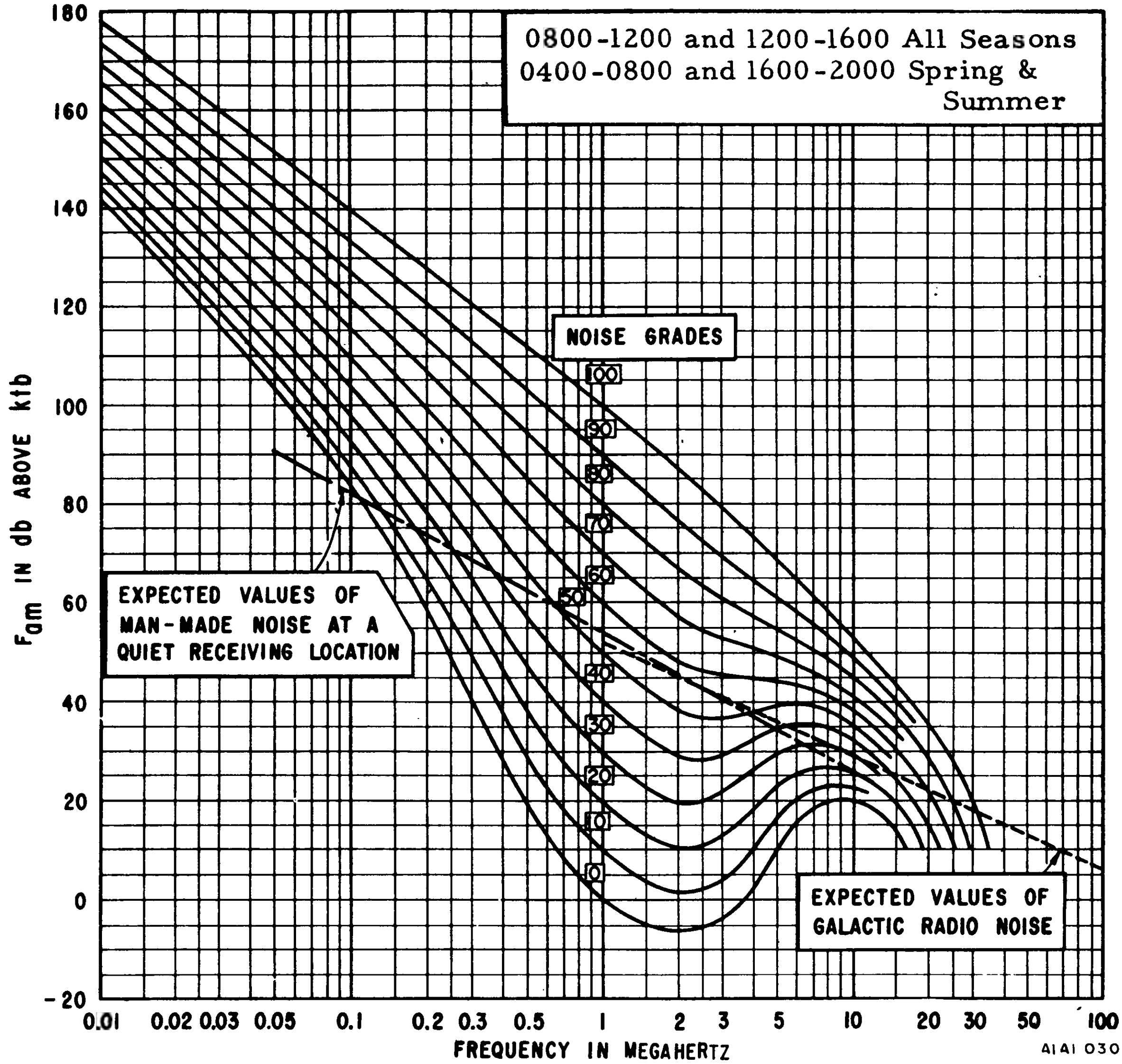


Figure 2-36. Time Block Median Values of Radio Noise Expected for a Short Vertical Antenna

o The "method of blanking" is used by means of a gate which opens or short circuits the receiver input under the influence of strong impulsive interference.

2.5.4 Noise Data and Predictions

Predicted levels of spherics for frequencies of 10 kHz and higher are representative samples of which are in Appendix A. Noise measurements in the VLF/LF bands are probably more reliable than those at medium and high frequencies (MF and HF) since it is usually much easier to find adequate channels for recording purposes at the lower frequencies, and recording bandwidths are closer to those used for communications. Noise measurements are, however, frequently contaminated by station interference.

The predictions contained in Appendix A are based on a relatively small amount of measured noise data. It is thus advisable to give considerable weight to recent noise measurements when they are available for an area under study.

a. Use of Predictions. The predicted noise level is obtained as follows:

o Select the season and time of day for which a prediction is desired.

o Refer to the map (Appendix A) that covers the season and time selected in (1). Map labels are in local time.

o Locate the receiving site on this map and determine the noise value at 1 MHz by interpolating between the contour lines.

o Refer to figure 2-37 and 2-38. Select the proper graph according to time of day and season. The 1-MHz noise value obtained above indicates the "noise grade" curve to use on these figures; locate the desired frequency along the bottom of the graph and follow the vertical line to the point of intersection with this noise grade curve. The horizontal line at this point indicates the median value of noise at the desired frequency, for a particular four-hour time block and season.

The values given on the graph are in terms of F_{am} or the median value of F_n. F_n is the noise power available from an equivalent lossless antenna in dB above ktb (the thermal noise power available from a passive resistance) where:

k = Boltzman's constant (1.38×10^{-23} joules per Kelvin)
t = Absolute temperature (taken as 288^oK)
b = Bandwidth in hertz

F_a in dB is related to the root mean square (rms) field strength at the antenna by the following equation:

$$E_n = F_a + 20 \log_{10} f_{MHz} - 65.5$$

where E_n = the equivalent vertically polarized ground wave rms noise field strength in dB above 1 mV/M for 1 kHz bandwidth f_{MHz} = the frequency in MHz.

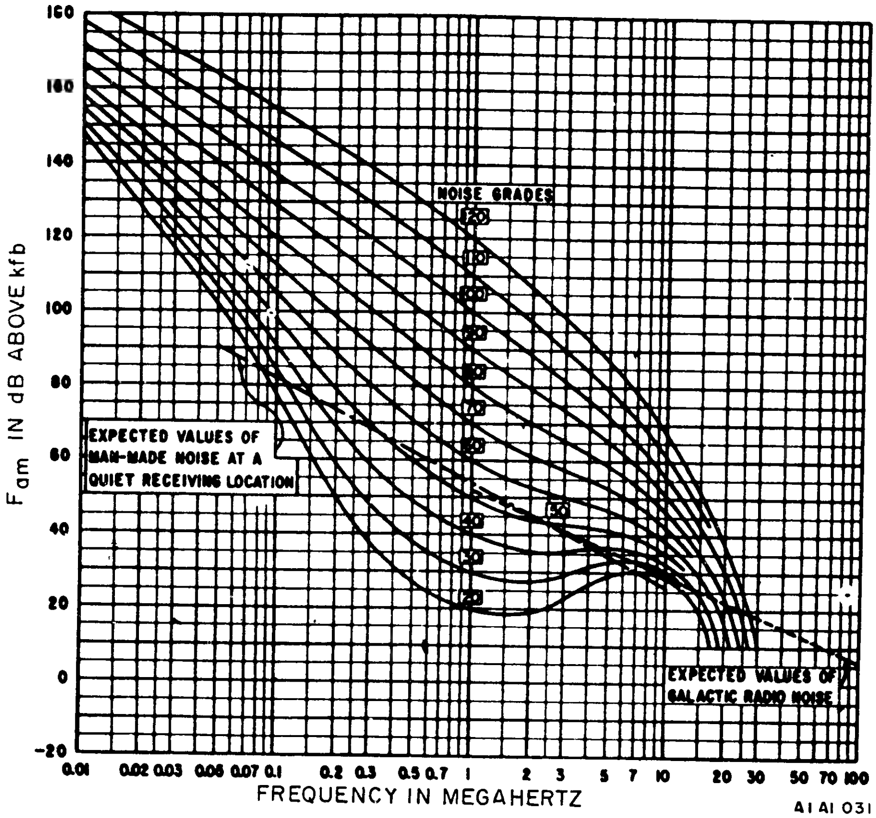


Figure 2-37. Median Values of Radio Noise (for a Short Vertical Antenna), Time Blocks:
0000-0400 and 2000-2400 Hours - All Seasons;
0400-0800 and 1600-2400 Hours - Autumn and Winter

NOTE

It is assumed that the rms noise field is proportional to the square root of the bandwidth.

The nomogram of figure 2-39 may be used for converting F_a to E_n. Draw a straight line connecting the points which represent the frequency and value of F_a; where the extension of this line intersects the E_n scale read the equivalent value of field strength. (This value is for a 1-kHz bandwidth; a correction must be applied for other bandwidths. For example, 8 dB must be added for a 6 kHz bandwidth.)

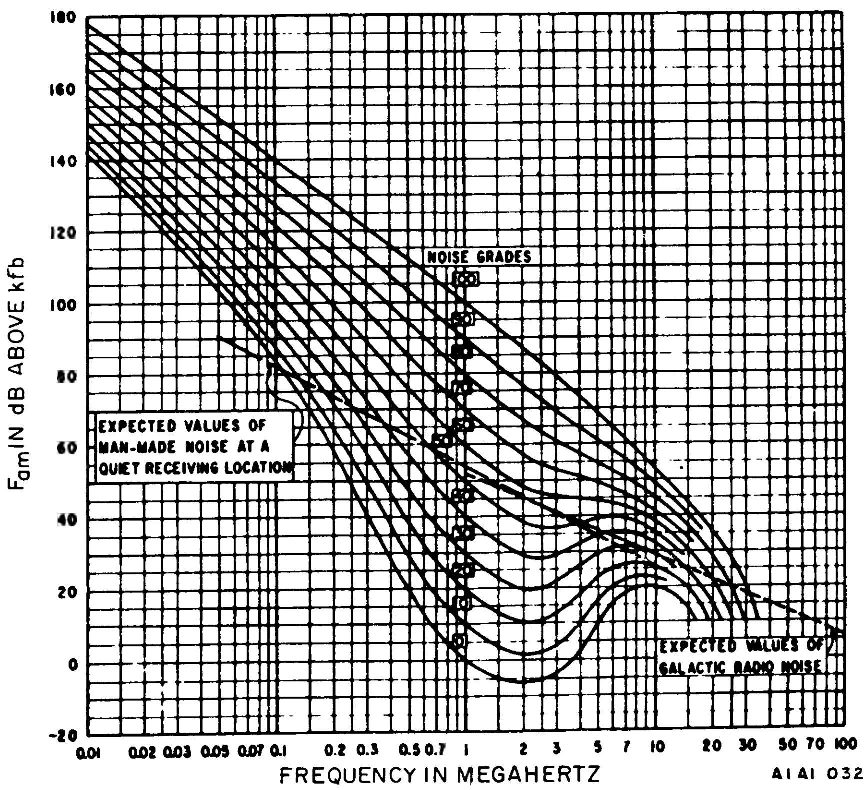


Figure 2-38. Median Values of Radio Noise (for a Short Vertical Antenna), Time Blocks:
0800-1200 and 1200-1600 Hours - All Seasons;
0400-0800 and 1600-2000 Hours - Spring and Summer

Since the predicted value is a median for a four-hour time block in a three-month season, allowance must be made for variations of the noise about this figure. An estimate of the value likely to be exceeded 10 and 90 percent of the time may be obtained from figure 2-40.

During sunrise and sunset (0400-0800 and 1600-2000) large and rapid changes in noise level may occur, particularly in the middle and upper part of the LF band. It may be desirable in specific problems to reconstruct the diurnal noise from the predicted median data, allowing for the time of occurrence of local sunrise and sunset. For locations at the equator it is suggested that the average of the levels obtained from the day and night curves, figures 2-37 and 2-38, be used during these periods (0400-0800 and 1600-2000).

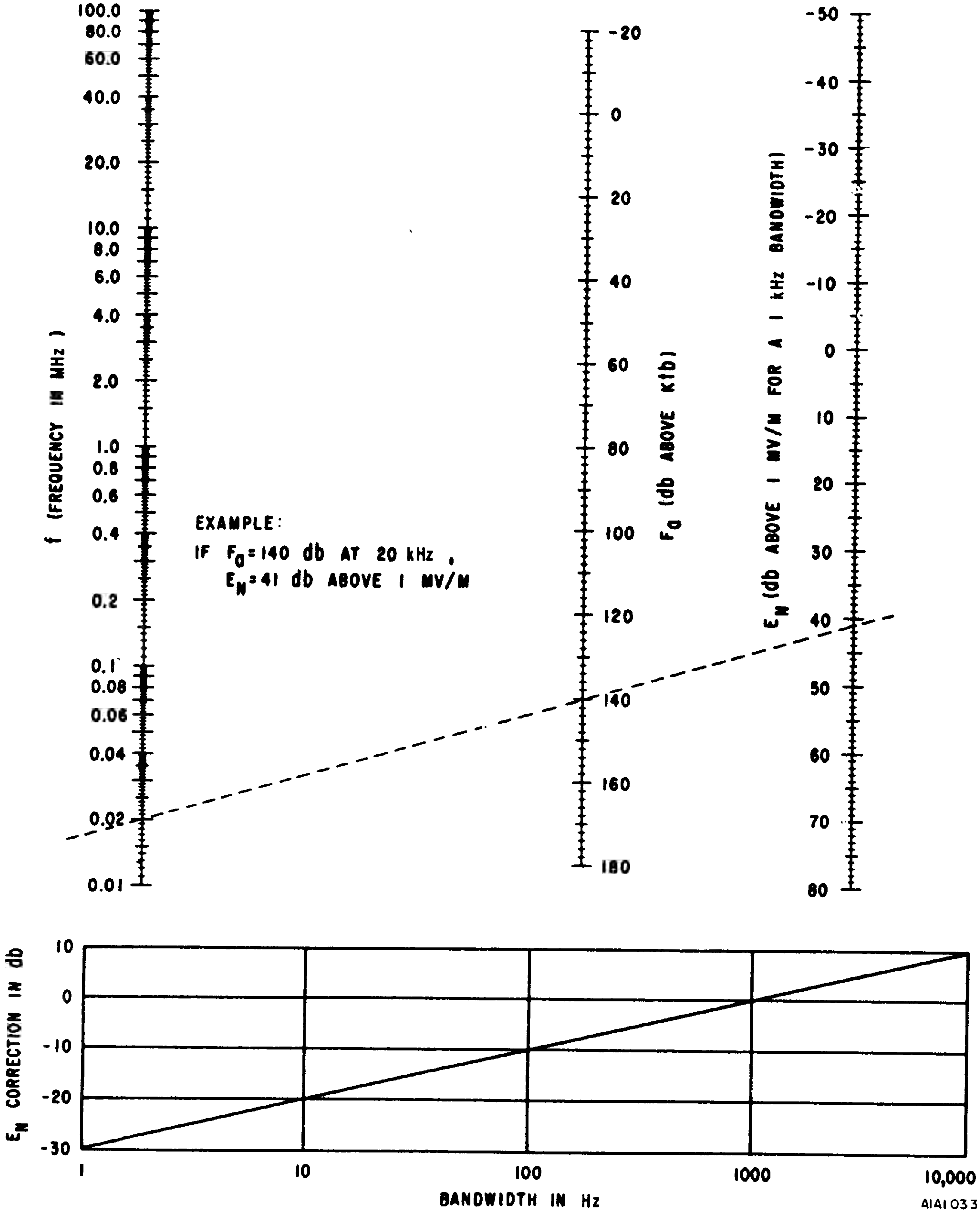


Figure 2-39. Nomogram for Transforming Effective Antenna Noise Figure to Noise Field Strength as a Function of Frequency

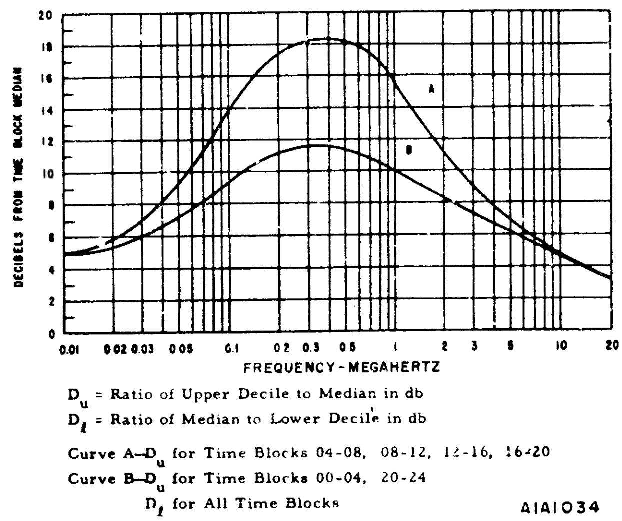


Figure 2-40. Expected Noise Level Variations From Time Block Median

The diurnal curves shown in figures 2-29 to 2-33 may be used as an aid in estimating the variation of noise during the sunrise - sunset periods, but may not be representative of diurnal trends except in the immediate area of measuring stations.

If the predicted spheric grade curve (figures 2-37 and 2-38) is lower than the man-made noise curve (at the desired frequencies) then it should be expected that during the times of day and/or season when atmospheric noise is at its lowest level the limiting factor may be man-made noise. As previously mentioned, it should be possible to reduce man-made noise below these predicted levels if care is used in the choice of a receiving site, and in minimizing man-made noise at that site; however, if it will be necessary to operate close to high-voltage power lines or unshielded ignition systems and industrial machinery the man-made noise levels can be expected to be even higher than those indicated by the man-made curve on figures 2-37 and 2-38.

b. Example of Noise Level Determination. For purposes of illustration, suppose that an estimate of radio noise at 20 kHz in the area near Hong Kong, China is required. The approximate location of Hong Kong is 22° 25' N and 114° 15' E.

o Use of Charts. Referring to figure A-1, the 1 MHz noise grade for the night hours (2000-2400 and 0000-0400 local time) is 70 in December-January-February and, from figure A-11, about 85 in June-July-August. On figure 2-37 follow the 70 and 85 noise grade curves (sketch in the 85 curve if desired) to find the 20 kHz values

of about 144 and 152 dB above ktb, respectively. The predicted levels for other seasons and times of day are found in similar manner, using the pertinent maps and frequency-conversion graph.

o The 1 MHz value at Hong Kong for 0800-1200, for example, is 23 in December-January-February and 40 in June-July-August, which gives 20 kHz values (from figure 2-38) of 133 and 140 dB above ktb, respectively. From the nomogram, figure 2-39 the field strength (E_n) equivalent to 140 dB above ktb (at 20 kHz) is 41 dB above 1 MV/M for a 1 kHz bandwidth, or 49 dB for a 6 kHz bandwidth. From figure 2-40 the expected value of D_u and D_e at night is about 5 dB, and during the day D_u is about 1 dB higher. Thus, for 0800-1200 in June-July-August, the median value for 20 kHz at Hong Kong is 140 dB, the value exceeded 90 percent of the time is 140-5 or 135 dB, and the value exceeded 10 percent of the time is 140 + 6 or 146 dB.

2.5.5 Signal-To-Noise Ratios (SNR)

Once the probable noise level for a particular location or area has been determined, it may be compared with the signal level computed for the desired path and an SNR established for a particular type of service under specified conditions of propagation and instrumentation.

The minimum signal power for satisfactory reception is:

$$P = \bar{F} + R - 204 + 10 \log_{10} B \tag{2-6}$$

where:

P = available signal power in dB above 1 watt
$\bar{F}$ = overall effective antenna noise figure in dB
R = required signal-to-noise ratio in dB
B = bandwidth in hertz

Studies have been made of the relationship between various signal-to-noise power ratios and the performance of certain radio systems; however, it is not yet possible to establish definite performance standards because the criteria for satisfactory operation may vary from system to system, even in systems of the same general type. For some systems the peak values of the noise pulses, their duration, and rate of occurrence are more important in determining the interference effects than is the average noise power level. There also are several impulse noise reducing techniques which will materially improve over-all system performance under given conditions of noise.

There is no precise method available for determining the effect of noise on a particular system short of a field test with that system under measured conditions of noise. Data obtained in this manner reflect the performance capabilities of the system only if the noise remains constant during each sampling interval, a condition difficult to obtain in practice, particularly when there are relatively local noise sources. However, once a system has been tested under measured noise conditions, it should be possible to obtain useful estimates of the performance to be expected at other locations or in other seasons, based on the noise data presented in this chapter.

In estimating the effects of noise on system performance, refer to chapter 4, which contains data on the distribution of time between pulses and the amplitude distributions of VLF noise envelopes. These data are not necessarily typical of the particular zones, and season, but do illustrate the wide variability to be expected in different areas, as well as the changes in dynamic range and level which generally result from reduction of the bandwidth. Chapter 4 contains information on the performance of two representative VLF systems as related to the carrier-to-noise average power ratio.

2.6 LIMITING NOISE AND INTERFERENCE

Atmospheric noise (spherics) are the most troublesome noise encountered in VLF and LF. Spherics are usually understood to be that radio noise energy radiated from lightning strokes. Spheric intensity diminishes at higher frequencies and becomes almost non-existent at VHF and higher.

In general, spherics are quite impulsive in character because of the short duration of individual lightning strokes. The dynamic range in field intensity between individual noise pulses at a given location may be over 100 dB because one pulse may have resulted from a lightning stroke only a few kilometers away while the next may have been propagated from a stroke half way around the world. Also, as might be expected, the time spacing between pulses is quasi-random. (See figures 2-41 through 2-43).

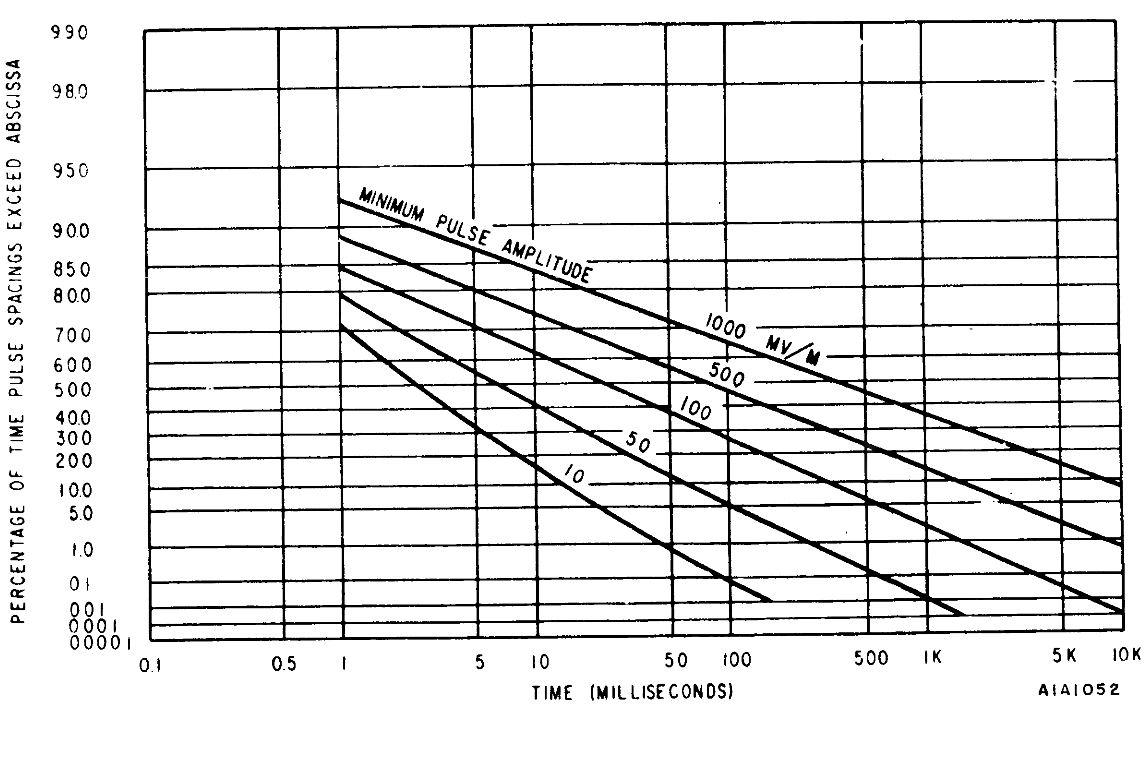


Figure 2-41. Distribution of Time Between Pulses of VLF Spherics in the Arctic (Autumn)

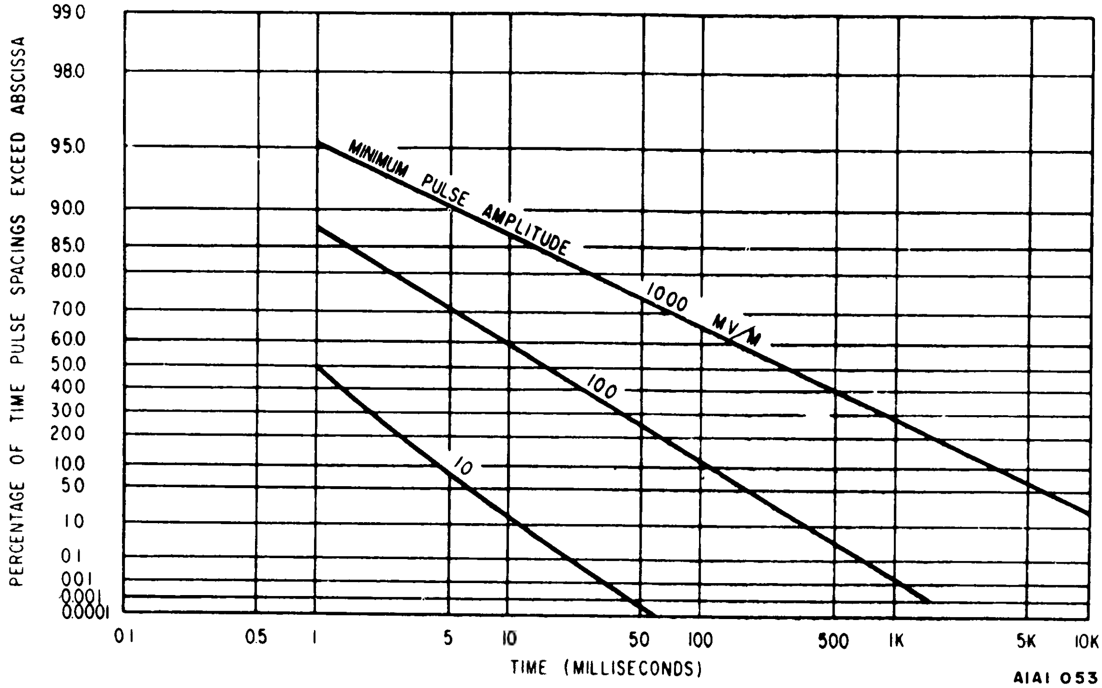


Figure 2-42. Distribution of Time Between Pulses of VLF Spheric in the Temperate Zone (Autumn)

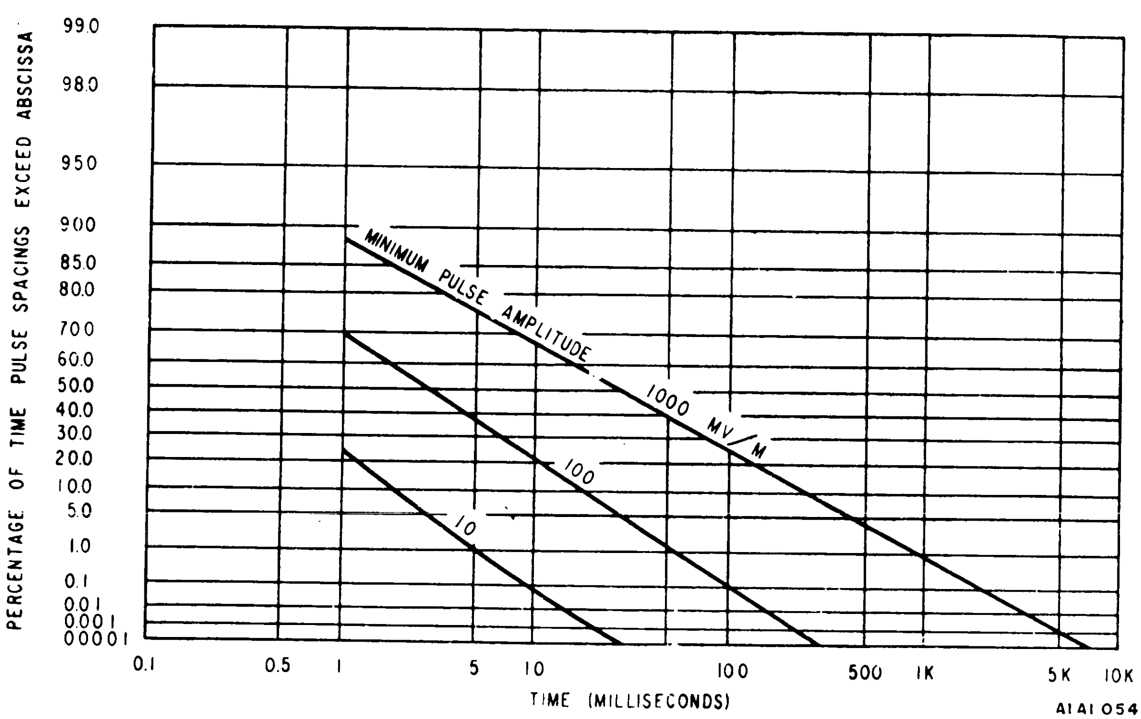


Figure 2-43. Distribution of Time Between Pulses of VLF Spheric in the Torrid Zone (Autumn)

Another general condition concerning atmospheric noise is that its level is higher in the northern hemisphere from March to September than from September to March. In the southern hemisphere, the high and low periods are reversed. This is because thunderstorm activity follows the summertime season from hemisphere to hemisphere.

Figures 2-44 through 2-46 indicate some of the trends mentioned above. Each figure depicts noise field intensities versus percentage of time the envelope of the noise amplitudes exceed given values. Although these data are not necessarily typical for these locations and time of year (since noise conditions vary over a rather large dynamic range from time to time) it is apparent that the noise level is very high in tropical latitudes near large thunderstorm centers.

Man-made noise originates from many sources to produce interference in the VLF and LF bands. The following are a few: ignition systems, corona from high voltage power lines, leakage of current across faulty insulators on power lines, commutation in generators and motors, switching transients on power circuits, arc-lighting systems, arc welding, electric railways and trolley busses, fluorescent lighting systems, and many forms of radio systems, especially those using pulse modulation. Generally man-made noise is much less than atmospheric noise at receive locations.

As is the case of spherics, most man-made noise is strongest at the lowest frequencies because so much of it is associated with power lines or rotating power equipment.

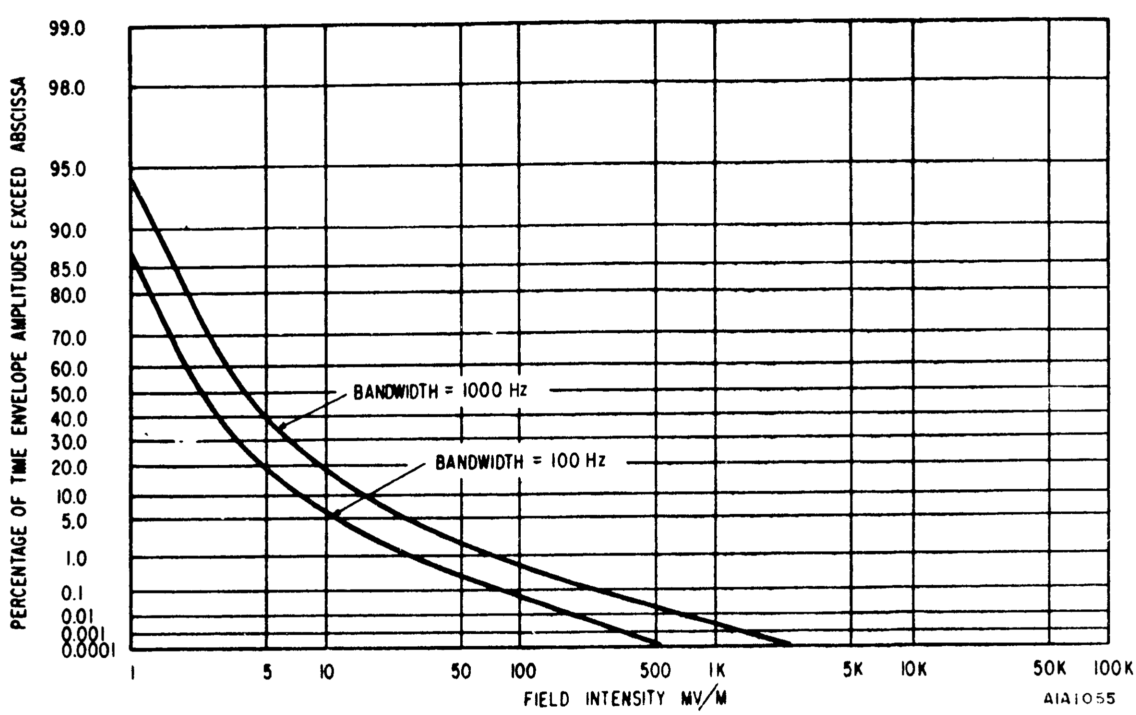


Figure 2-44. Field Intensity MV/Meter, Arctic (Autumn)

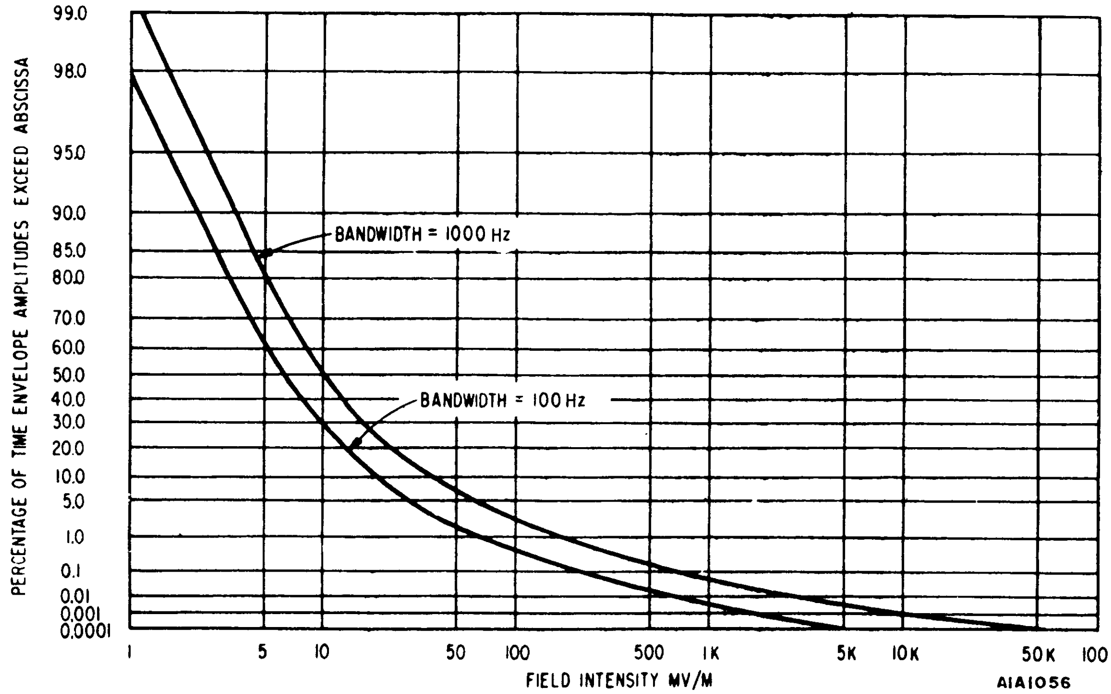


Figure 2-45. Field Intensity MV/Meter, Temperate Zone (Autumn)

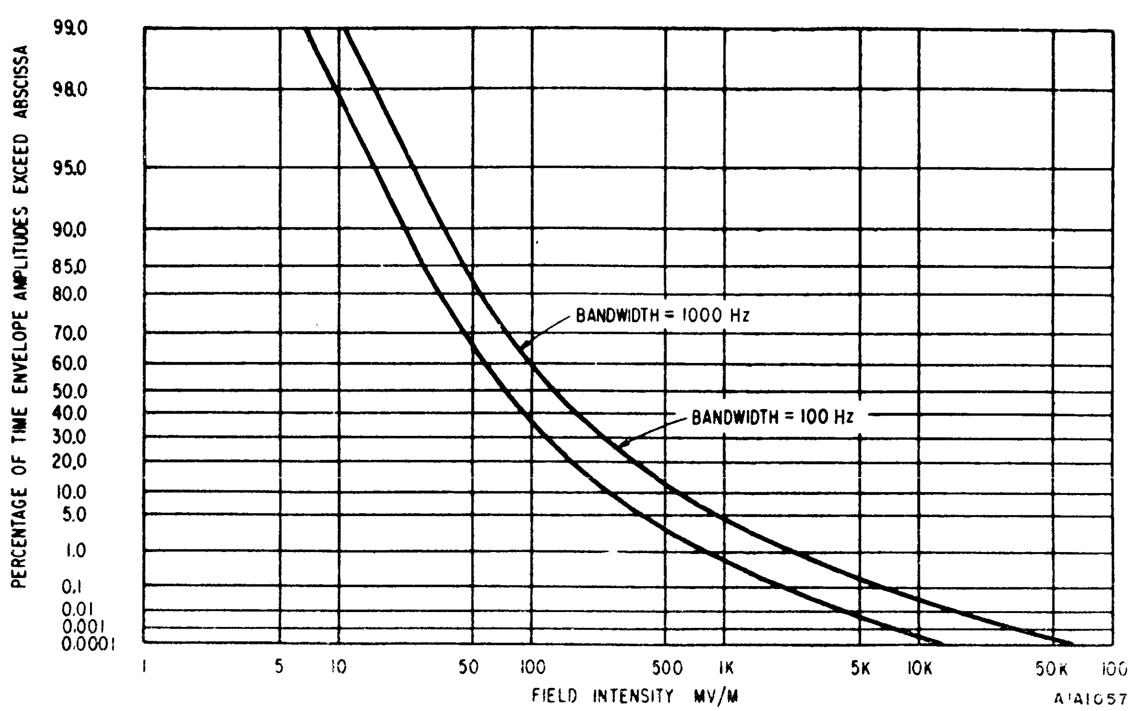


Figure 2-46. Field Intensity MV/Meter, Torrid Zone (Autumn)

2.7 RELIABILITY AND PROPAGATION LIMITATIONS

2.7.1 Reliability

From the discussion of normal propagation variations, disturbances, and noise, we conclude that variations in the intensity of natural noise represent the greatest source of variability in required transmitter power. For quantitative discussion, we take the curve labeled "polar transmitter" in figure 2-40 as representative of the power requirements for reliable transmission to any part of the globe. Even for Morse code at 12 wpm, the required ERP is 100 megawatts, or 30 dB greater than the power radiated by present VLF transmitters.

With existing power of 1000 kW, transmission to some sites of the world will occur on occasion, but with reduced reliability. For example, if we accept a 10 percent error rate for 12 wpm Morse code on only 50 percent of the hours of the day, we can save nearly 20 dB ($T_X = 0$, $C/N_{ikc} = 11.5$ dB).

We can gain another 10 dB by considering only receiving situations where spherics are 10 dB below maximum. Since the median polar noise fluctuates through 10 dB and in the tropics over 20 dB, it is possible to realize 10 percent error transmission on 50 percent of the hours at any location during some parts of the year.

Since the power required for even a very low speed (12 wpm) reliable system is prohibitive, some new approach is needed. As previously mentioned, the best hope is through improved receiving techniques, in which optimum noise suppressors and antennas are used. It is possible that the extra 30 dB required for 12 wpm Morse code with one percent errors can be obtained; but 60 wpm TTY requires about 40 dB improvement in SNR for worst conditions, and this may be difficult to realize in practice. However, if we allow the error rate to increase from one percent to 10 percent we can gain 10 dB. In practice, one might then arrange to increase message redundance during periods of high noise at the receiver.

The SNR at the receiver as a function of transmitter location must be considered in addition to the obvious importance of locating the transmitter in a region of high ground conductivity.

The optimum location can be determined only when the improvement produced by various kinds of noise-limiting circuits can be evaluated in the presence of the different kinds of noise found in different areas of the world. Since the statistics of noise appear to vary widely with location, it will be necessary to obtain new measurements of these factors before adequate data are available for such a determination.

2.7.2 Propagation Limitations

Because of the reliability of low-frequency (LF) (and particularly VLF) radio signals, they are extremely important for long range communications and for world-wide standards of time and frequency. However, there are some disadvantages in the use of these frequency ranges which greatly offset some of the advantages. As a result, their use is very limited when compared to the numerous applications made of higher

frequency radio energy.

At VLF, the ground wave field intensity diminishes inversely as the distance up to about 500 km over sea water and ground of good conductivity; for ground of good conductivity, the inverse distance holds true to about 200 km. At LF the same rules apply, but the distances are reduces to about 300 km and 15 or 20 km respectively; the losses in poor ground rise rapidly with increasing frequency. At distances well beyond those given above, the ground wave diminishes at a faster rate because of significant absorption and becomes negligible at long distances.

At VLF, the ionosphere is a rather good reflector because the penetration depth becomes a small fraction of the very long wavelength. This results in a skywave which is strong enough to support radio communications at great distances with VLF both day and night.

The same general effects apply to LF at night so that long-distance communication may be quite reliable, but during the daytime, the ionospheric absorption increases to a serious extent, particularly in summertime. The absorption rises rapidly with frequency also. It becomes clear that the lowest radio frequencies suffer the least attenuation and time varying fading at great distances and therein lies their great advantage for long-range radio communication.

o Amplitude. To the long waves involved in VLF and LF signals, the day or night ionosphere appears as a rather smooth-surfaced stationary reflector in contrast to the variability it exhibits to short radio waves. The relative time stability of this reflector causes the field intensity of the sky wave to be free from rapid fading for VLF, and nearly free for the upper limit of LF except at night. The fastest fades for LF have a period of several minutes at night. Slow changes in ionospheric absorption also produce correspondingly slow changes in field intensity of the sky wave and this usually requires about an hour.

Rather deep fades occur at points where the sky waves and ground wave can substantially cancel each other. The cancellation points are relatively stationary at VLF, but move in and out as the ionospheric height or absorption changes. When the sun is rising or setting on the ionosphere along the path the points move rather rapidly and deep fades lasting a few minutes usually occur twice a day.

o Phase and Frequency. The discussion above on amplitude stability also applies to phase and frequency stability. The smooth appearance of the ionosphere to long radio waves and its relatively slow variations produce no short-term effects on phase and frequency except during the sunrise or sunset amplitude fades which occur.

2.8 FREQUENCY CONSIDERATIONS

2.8.1 VLF Considerations

The VLF spectrum is nominally defined as 3 to 30 kHz, but the usable band is confined to the range of 10 to 30 kHz. This is largely due to the difficulty in building efficient transmitting antennas for such wavelengths (10 km $< \lambda <$ 30 km). The propagation is characterized by relatively low path-attenuation which is relatively stable with time. This feature, plus the fact that VLF energy is guided for long distances (5000 to 20,000 km) between the earth and ionosphere, makes VLF attractive for long-distance paths when high reliability is important. Noise at VLF is very high in most areas of the world, and, as a result, high transmitter powers are required. For a geographically fixed transmitter and receiver communication system, an optimum frequency is selected with respect to the signal-to-noise ratio (SNR) requirements at the receiver location. For a broadcast communication system, such as that used by the Navy, the selected frequency will depend on the coverage area required and the predominent frequency distribution and levels of the spheric in this area. The spheric levels are relatively low in the polar regions, however, polar ice attenuation such as provided by Greenland or Antarctica is extreme in daytime.

A statistical approach may be taken in arriving at the SNR required to maintain a TTY copy accuracy of 99.9% for 50% and higher confidence limits, using signal characteristics suitable for VLF and measured noise.

2.8.2 LF Considerations

The primary consideration in determining the operating frequency for an LF transmitter site is the frequency allocation available for the station and height of the antenna. The antenna height, type of top loading, and operating frequency are the limiting factors in achieving the required antenna efficiency and bandwidth. A minimum antenna system efficiency of 50% is the design goal for LF transmitting antennas. A transmitting system bandwidth of 1700 Hz is required for the eight channel fleet broadcast while single channel system required bandwidth depends upon mode of modulation and mode characteristics. For the stations with optimum toploading on 600-foot towers, frequency of operation should be above 85 kHz. Since navigation assignments eliminate the 90-110 kHz band from consideration, there is only a small range below 110 kHz available for the 600-foot antennas. If the existing 800-foot antennas are loaded with 24 topload radials, frequencies down to 69 kHz can be assigned to stations having these antennas. It is probable that structural limitations will preclude full toploading and in this event the lower frequency may be as great as 75 kHz. If operation below this frequency is required, much larger structures must be considered to provide acceptable efficiency. In some locations it may be necessary to use still smaller antennas, such as a 360-foot type. This approach is acceptable if frequencies above about 125 kHz are assigned these stations.

Another consideration in frequency assignments is that of geographical location. Based on preliminary computations involving the multichannel LF broadcast, it was found that in the tropics a high operating frequency is best, because atmospheric noise is higher at lower frequencies. At Balboa, for instance, 500 kHz would be preferable to a frequency in the 50-150 kHz band; this is a result of coverage within short ground-wave range so that signal attenuation is not a function of frequency while noise decreases with frequency. For temperate zones the expected range is greater and there is a compensating effect, in that signal attenuation increases, while spherics decrease with frequency. No clear optimum is indicated over the 50 to 150 kHz band in the temperate zone. In high latitudes noise data are sparse and it is not clear whether the optimum is nearer 50 kHz during normal ionospheric conditions. However, during disturbed conditions it is probable that frequencies well below 100 kHz would have less added attenuation and thus may be preferred. In general, higher LF frequencies should be used near the equator where spherics are greater; and lower frequencies for high latitudes where noise is less.

From the standpoint of SNR, the need for using frequencies below about 70 kHz is questionable. Accordingly, antennas higher than 800 feet (with optimum toploading) should not be considered essential except at stations where lower frequencies have been assigned because higher frequencies are not available. Since single-channel operation will be required for some time to come, and since the bandwidth needed is much less, the lower frequency assignments could be used for this purpose. If it is imperative from an assignment standpoint to use frequencies below about 70 kHz for multichannel broadcast, it is recommended that a much larger antenna be designed for these particular stations. These should be used in low-noise areas insofar as practicable, for the reasons discussed above.

The level of atmospheric static increases as frequency becomes lower, and this factor normally controls the effectiveness of LF communication. Although the strength of the transmitted wave remains relatively steady, the spherics with which the signal competes may vary over 20 decibels throughout the day. Local thunderstorm activity may further increase this variation by another 20 to 40 dB. The range variation of the LF station is generally determined by the variation in local noise level rather than variations in signal level.

2.8.3 Other Considerations

Other considerations include frequency interference effects. For example, when the power of the Yosami VLF transmitter was increased in 1964, severe interference problems of its 17.4 kHz transmissions with the local 17.5 kHz telephone ringer systems resulted which were corrected only by crossing cable pairs on long lengths of telephone lines and by readjustment of most ringers. Obtaining a frequency clearance for radiation may be consideration in some overseas areas.

2.9 COMPUTER PREDICTION TECHNIQUES

In the last few years considerable effort has been directed to developing computer techniques for the prediction of VLF noise and propagation.

2.9.1 VLF Atmospheric Noise (Spheric) Prediction

A digital computer model for predicting the characteristics of spherics has been developed under the sponsorship of Naval Research Laboratory. The model provides for the calculation of mean values of atmospheric noise and/or signal vertical electric field intensity; the standard deviation from the mean values; mean values for voltage deviation, V_d; and the direction of arrival of the noise energy. The model calculates values for any location on the earth at any frequency from 10 to 30 kHz.

Five algorithms which form the basis for the model have been developed.

o An algorithm for computing electromagnetic power radiated from every region of the earth. Improved thunderstorm day maps and lightning discharge data provide the input to the computations.

o An algorithm for computing the standard deviation of power radiated for every region of the earth. Statistics of thunderstorm and lightning occurrence provide the data input to these computations.

o An algorithm for the propagation of energy within the earth-ionosphere waveguide. This algorithm, or model, includes the effects of ground conductivity, direction of propagation, latitude, sun zenith-angle and day or night path conditions. The three most significant modes of propagation are used.

o An algorithm which uses the results of the first three to compute noise field intensities (F_v), standard deviations (σ_N), V_d's and direction of arrival values for any location on the earth's surface, for any hour, any month and at any frequency from 10 to 30 kHz.

o An algorithm to take the output and prepare contour plots, polar plots, diurnal plots, frequency interpolation plots, and data inputs to computer programs for communications system analysis.

The prediction model was used to compute E_v, σ_N and V_d at 20 kHz, in a 1 kHz bandwidth, for every 10^o longitude and every 10^o latitude (from 80^o S to 80^o N). These were computed for each hour and month and were used in the preparation of contours for noise prediction maps. Frequency interpolation plots, for interpolating values from the 20 kHz prediction maps to any frequency from 10 to 30 kHz were prepared. Plots were made for each season, every fourth hour, to represent each of 34 regions of the earth. The bulk of the calculations, contour plots, etc. were used in the preparation of a VLF spheric prediction manual to be published by the United States Government.

The use of the model to prepare a VLF atmospheric noise prediction manual has resulted in the availability of noise prediction maps for the entire world for each hour and month, for field intensity and standard deviation values. Voltage deviation, V_d, prediction maps are available for each hour and each season. Frequency interpolation curves provide the ability to interpolate the 20 kHz values on the maps to any frequency from 10 to 30 kHz, for each season and for 34 approximately equal area

regions of the earth. Standard deviation, V_d, and frequency interpolation data as a function of geographic location are also provided. (Previously the estimates for these parameters had been average values supposedly valid for the entire world.)

2.9.2 Multimode Propagation Prediction

Parallel to the development of the atmospheric noise computer model, the Naval Research Laboratory (NRL) developed a computer model of Singlemode Propagation Prediction.

The model presently being used by NRL to predict signal-strength levels applies statistical concepts to available VLF propagation data. The predicted signal statistics are derived from an assumed normal distribution of hourly signal levels for the day-to-day signal variation occurring during any particular month. The "median" parameter for the normal distribution is calculated by using mode equations from J. R. Watts (1956) theoretical-waveguide propagation model for a single-mode propagation prediction. In actuality, the propagated signal fluctuates in a complex manner as a function of distance from the transmitter and as a function of the ionospheric conditions. Since such changes are not predicted in the current NRL propagation model, major deviations can occur between the real signal levels and those predicted by the model. Therefore, it is important that a method be devised that will provide communicators and systems planners with information concerning the nature, magnitude and geographic locations of regions of low signal level and of large signal variability. Since the large fluctuations in field strength as a function of distance that occur in VLF propagation are due to multimode-interference characteristics, a concept that uses a complex multimode model to compute the VLF propagation field levels should improve the quality of predictions.

An accurate detailed theoretical model of multimode propagation has been developed in recent years by NELC (Pappert et al., Radio Science 2, 4, 1967). This model can account for the large signal-variability that occurs with increasing distance as illustrated in figure 1-3 (page 1-19). This close agreement has been demonstrated for many paths, frequencies and for both day and night. (Bickel et al., Radio Science, 5, 1, 1970). These multimode models provide a major improvement in the state of the art of VLF theory and prediction capability. However, the computed results are sensitive to the choice of ionospheric model parameters used as inputs for the calculations. For example, the position of the model interference pattern at 3000 to 4000 km range shift about 200 to 300 km when the ionospheric height changes by 2 to 3 km. The shift is a linear function of distance. This is the degree of ionospheric variability which has been observed at mid-latitudes at night. The daytime D region ionosphere is much more stable and predictable and is known to vary with latitude, season, and solar zenith angle. The latitude and seasonal variation of the nighttime ionosphere is less well known. Since the ionosphere itself is sufficiently variable, the ability to make a precise prediction of propagation parameters such as exact null depth and position at a given time is limited. However, the exact theory can be used to examine such things as: the optimum frequency separation to use to implement frequency diversity, i.e., where the modal interference maximum of one frequency coincides with the modal interference minimum of another; or the frequency dispersion characteristics of the propagation medium to aid in developing modern match filter receiver systems.

Improvements in general coverage prediction have been devised by using this more refined multimode propagation model. Multimode-prediction computations have been made and a mean single mode equivalent (ESM) signal level along radials at various azimuths from a given transmitter is determined. Once the values of mean ESM signal and multimode signal variability about the ESM (as functions of range and direction from the transmitter) have been determined for each frequency of interest, contour charts of field strength are constructed. Equivalent single mode models similar in appearance to those used in the present NRL single mode coverage charts have been developed. The variability is used to determine the level exceeded a large given percent of the time (distances, etc.). This method of generating general coverage information is useful for filling in gaps where propagation data is not available, i.e., for other frequencies or directions of propagation relative to the earth's magnetic field. The equivalent single mode approximation is used to represent the smoothing of the multimode field because there is not always one waveguide mode which is always dominant, especially at the higher end of the VLF band and above.

The dominant parameters affecting field-strength levels (other than electron-density profile) are those related to the earth's magnetic field. These are the magnetic azimuth of the direction of propagation and the magnetic dip angle along the propagation path. The values of these parameters are particularly important when computing nighttime field strength. Signal levels computed in many radial directions from a transmitter have been used to construct contour maps derived from the multimode field-strength values. These maps give the NELC prediction of signal-level coverage that is available for the transmitted VLF or LF frequency of interest. These contour maps show the effect of magnetic field variation on VLF/LF signals.

The quality of coverage prediction, both equivalent single mode approximation and detailed multimode fields, is directly dependent on the state of knowledge of the lower ionosphere and its variability, both systematic and random. This knowledge is presently limited and can only be acquired by extensive diagnostic measurements. VLF/LF multifrequency-sounder measurements and measurements vs. distance using aircraft have proved to be the best source of data for establishing ionospheric and propagation parameters.

2.10 DIGITAL SIGNALS

2.10.1 Amplitude Modulation (AM)

Because of the narrow band encompassed by the entire VLF and LF range, the spectrum must be very carefully conserved by using very narrow channels.

VLF transmitting antennas with their tuning equipment inherently have very high Q's; LF antenna Q's are somewhat lower. In general, high Q in a circuit causes it to have a narrow bandwidth, therefore these factors, high Q and low bandwidth, require narrow channel bandwidths.

Narrow channels cannot transmit high information-rates because of intersymbol interference, or the inability of the channel to accommodate rapid transitions in carrier amplitude, frequency, or phase.

This limits VLF transmissions to low information rate applications. It also limits the transmission rate for LF, but to a lesser extent for the higher frequencies.

Because VLF transmissions suffer such serious disturbances from spherics, it is not practical to amplitude-modulate the radio carrier by small and varying amounts.

On-off keying of a carrier wave lends itself to Morse Code. Short periods of transmitter keyed on signify dots; long periods of transmitter keyed on signify dashes. The usual keying rate is about 15 words per minute (wpm) because it copies well aurally, and because this rate corresponds to a comfortable upper limit for the average radio operator in the presence of noise. A semi-automatic system using International Morse Code is capable of much higher keying and receiving rates. Keying is by machine, and copying is graphic for later decoding by the human operator. However, the keying rate is generally limited by the transmitting antenna Q as previously mentioned. Morse Code is also used extensively in the LF range. Coded signals as navigational aids for aircraft are also common in the LF band.

2.10.2 Frequency Modulation

When frequency modulation is accomplished at discrete levels, it is referred to as frequency shift keying (FSK). Two-level FSK is readily adaptable to Morse Code, but very little or no application has been made of it to date because, when FSK came into being, interest was centered on automatic TTY systems.

Figure 2-47 shows the basic performance of an FSK binary-digit system for thermal and spheric disturbances. Curve A indicates that there is a distinct threshold effect for thermal noise. For example, by increasing the carrier-to-noise ratio by only 7.0 dB, the probability in binary errors can be reduced from 1 percent to 0.0001 percent.

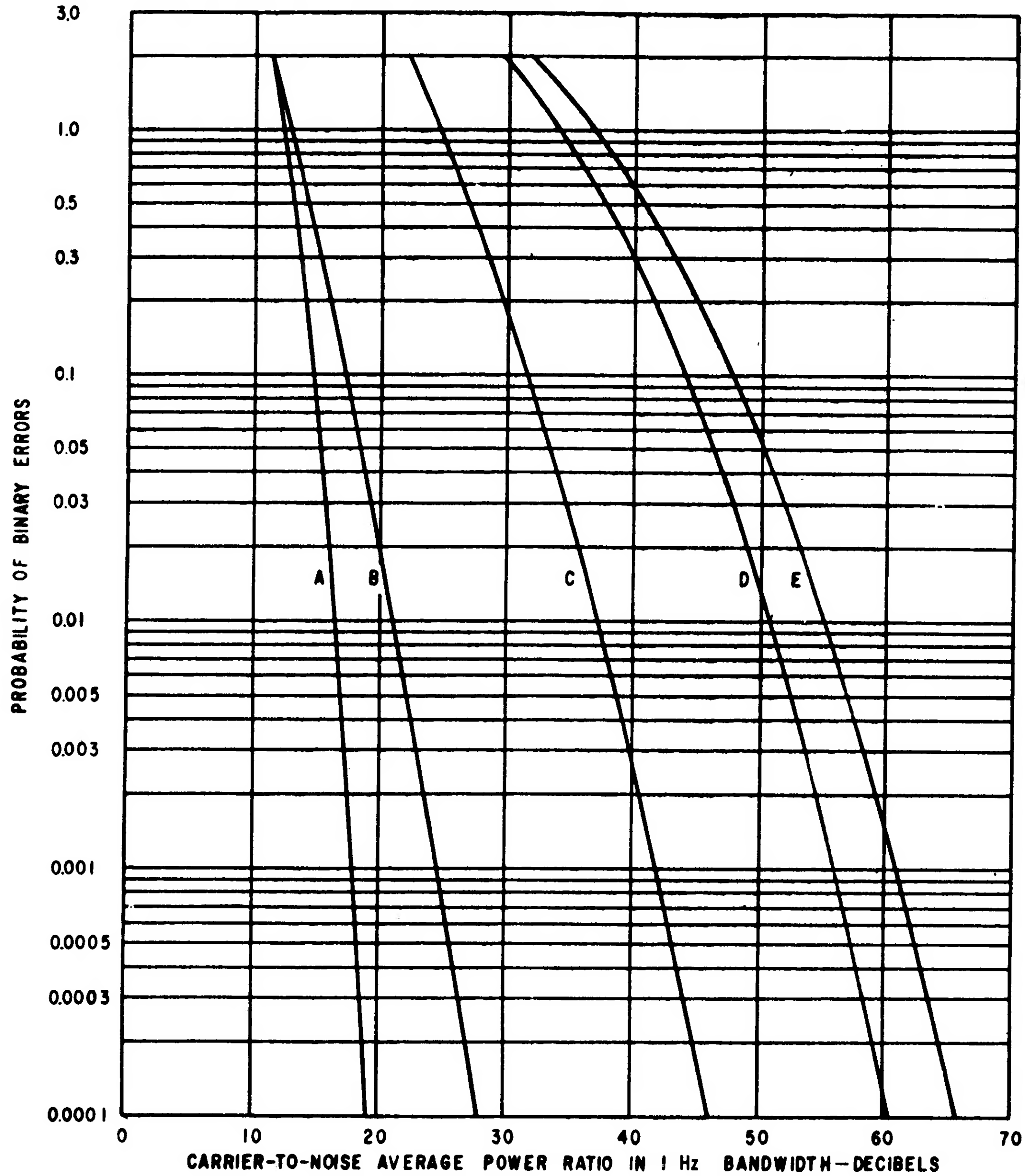
The dB difference between curve A and curve B indicates the increased power required to overcome spherics for the same transmission rate of one baud for the various probabilities in binary errors. For instance, at a probability of 0.01 percent binary errors, the power must be increased approximately 4.6 dB.

Curves C, D, and E are for 10, 50, and 75 baud respectively.

Figure 2-48 shows the basic performance of an FSK eight-unit interval start-stop TTY system.

Several impulse noise reducing techniques are effective in the presence of spherics which will effect a saving in transmitter power for a given probability of error. Some techniques are more effective than others; some of the more sophisticated ones carry security classifications. The above performance curves apply to systems not using any noise reduction methods other than good over-all system design.

Degradation-factors for spherics applied to similar systems operating in LF range have not been determined, but it is believed that they would be much like those shown because of the somewhat similar noise conditions to be found in the LF band.



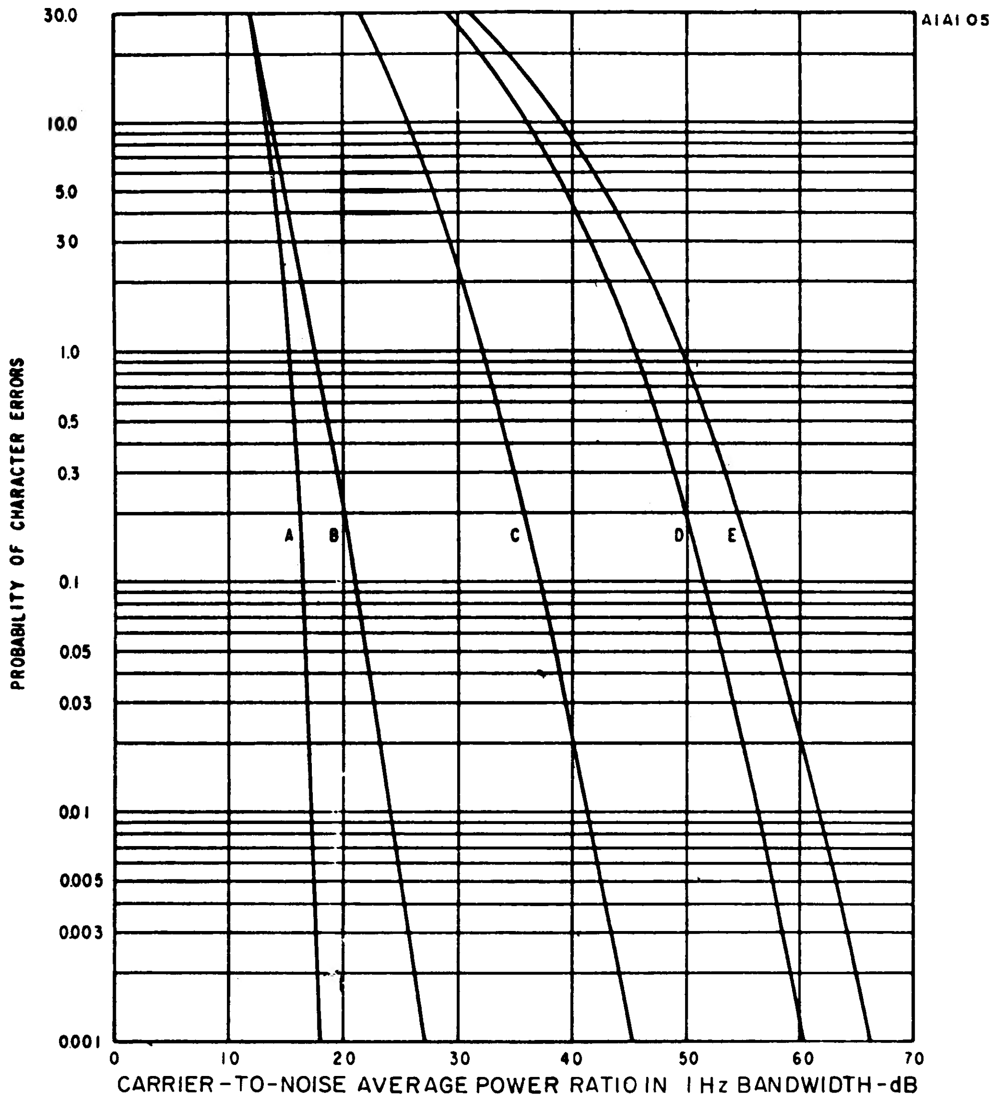
Modulation index $M = \frac{\Delta F}{f} = \frac{\text{carrier frequency deviation}}{\text{modulating frequency}} = 2.0$

(which is about optimum for this type of service).

Each system 6 db bandwidth in Hz is assumed to be 3.75 x baud rate.

A: error rate for 1 baud for thermal noise disturbance
B: error rate for 1 baud for atmospheric noise disturbance
C: error rate for 10 baud for atmospheric noise disturbance
D: rror rate for 50 baud for atmospheric noise disturbance
AIA1058 E: error rate for 75 baud for atmospheric noise disturbance

Figure 2-47. Performance of FSK Binary Digit System



Modulation index $M = \frac{\Delta F}{f} = \frac{\text{carrier frequency deviation}}{\text{modulating frequency}} = 2.0$ (which is about optimum for this type of service).

Each system 6 dB bandwidth in Hz is assumed to be 2.83 x word rate per minute.

A: error rate for 1 word per minute for thermal noise disturbance
B: error rate for 1 word per minute for atmospheric noise disturbance
C: error rate for 10 words per minute for atmospheric noise disturbance
D: error rate for 60 words per minute for atmospheric noise disturbance
E: error rate for 100 words per minute for atmospheric noise disturbance

Figure 2-48. Performance of FSK Eight Unit Interval Start-Stop TTY System

Multichannel angle modulation consists of two types: time division multiplex and frequency division multiplex.

Time division multiplex is used rather extensively for radio TTY. Such systems are usually synchronous, in contrast to the start-stop systems commonly used for single-channel systems. With synchronous operation, the start and stop pulses of the TTY code can be omitted, and bandwidths can be reduced accordingly. Such four-channel systems usually use a 6 dB bandwidth of about 500 Hz (only about three times the bandwidth required for single channel start-stop systems).

In view of the large bandwidth required to accommodate several channels, multiplexing is generally not practical at VLF because of antenna Q's and frequency allocations, but time division multiplex is used in the LF band.

Frequency division multiplex systems use subcarriers which must be protected with guard bands. Such schemes are extremely useful at high frequencies, but, since the guard bands are wasteful of spectrum availability, such systems are not applicable to VLF and LF.